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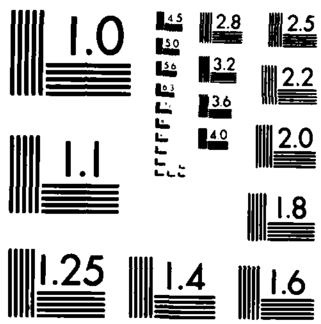

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A REPLENISHMENT PHASE STUDY FOR THE

NAVSTAR GLOBAL POSITIONING SYSTEM

THESIS

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A REPLENISHMENT PHASE STUDY FOR THE NAVSTAR GLOBAL POSITIONING SYSTEM

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Space Operations

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Major, USAF

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David J. Aderhold

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Abstract

A Q-GERT simulation model was designed to estimate the replenishment phase for the Global Positioning System using the original block buy of 28 satellites. Block I satellites were not considered in the study. The model determines the best fixed launch schedule without replenishment to find out when the initial constellation falls below 18 satellites. Additionally, the model was modified to determine the best fixed launch schedule that would maintain the constellation at 21 functional satellites 99% of the time.

Sensitivity analysis was performed on the parameters of satellite design life and reliability through final orbit insertion. Satellite availability curves were used to show the number of operational satellites over time. Point availability curves were used to display the fraction of 21 satellites available each month of operation.

A satellite attrition analysis was performed by selecting up to three satellites for deletion and evaluating coverage over the major land areas.

The Aerospace Corporation's EGAD Model was used to examine the performance of the Walker 18/6/2 plus 3 spares constellation. This threshold of 21 satellites became the design constraint for the simulation model of the system's operational phase over a 20 year period. A replenishment launch schedule was evaluated using a satellite design life of 7.5 years and a reliability through final orbit insertion of 94%.

A REPLENISHMENT PHASE STUDY FOR THE NAVSTAR GLOBAL POSITIONING SYSTEM

I. Introduction

Background

> The NAVSTAR Global Positioning System (GPS) is a space-based, all-weather, continuous-navigation system that provides extremely accurate position, velocity, and time information to users anywhere in the world. The program is managed by the Air Force Space Division as a joint program of all the services, including the Defense Mapping Agency, the Department of Transportation, NATO, and Australia (10).

The space segment of the GPS program is currently in the full-scale production phase with an operational buildup of the constellation due to commence in 1986 with full operational capability in 1988. The Aerospace Corporation, El Segundo, California, provides consultant services for the general systems engineering and integration for GPS. The current program involves a block buy of 28 satellites from Rockwell International and a baseline constellation of 18 satellites plus three spares.

There are several operational issues that Space Division is researching. One of the most important is to validate the baseline configuration of 21 satellites recommended by the Aerospace Corporation. This has been done using a mask angle of five degrees, but due to restructuring of the GPS program and a proposal by the FAA (6), a reevaluation of the constellation using a mask angle of 7.5 degrees is required. The

first area of study in this report will investigate the baseline configuration and three other configurations in order to determine a minimum operational number threshold of satellites in the constellation for worldwide continuous coverage.

Once the threshold number of satellites is established, Space Division must determine when the original block buy will need replenishment. This report will examine this important operational question and will estimate the time frame for replenishment as well as the number of satellites needed to operate the system over 20 years.

There are two important parameters used in this study--satellite design life and reliability through final orbit insertion. Current estimates by the Air Force Space Division for these two values are 7.5 years and 94% respectively (16).

There is currently insufficient historical data to substantiate the values for design life and reliability through final orbit insertion. Therefore, this research will benefit Space Division by providing a sensitivity analysis on these two parameters to determine their impact on the total number of satellites needed over 20 years and a replenishment launch strategy to maintain the system at a certain operational number threshold. For selected values of satellite design life and reliability through final orbit insertion, program cost estimates will be projected in FY 86 dollars. The program costs involve soft estimates of $74 Million per launch ($42 Million per GPS satellite, $6 Million for the Upper Stage, and $26 Million for Shuttle fee per satellite) (16).

Finally, the last area to be investigated is the assessment of the impact of satellite attrition. It is extremely important for users to have this operational information available for planning since a degradation in navigational accuracy may adversely affect a mission. A summary of the research in this study is provided.

- -- How long the current block buy will provide minimum operational performance.
- -- Determination of when the replenishment phase begins.
- -- The time frame and size of the next block buy of GPS satellites.
- -- Sensitivity analysis of satellite design life and reliability through final orbit insertion.
- -- Assessment of the impact of satellite attrition.
- -- Estimated operational cost over 20 years in FY 86 dollars.

These issues will be addressed within this report through the use of computer simulation. A computer model will be used to determine when the actual replenishment phase should begin. The model will simulate the launch, the activities through final orbit insertion, and operating life in orbit for a constellation of satellites. The primary output from this model is a histogram file that will be used to plot time versus the number of operating satellites. The time when the system falls below 18 functional satellites will establish the replenishment phase for the GPS program. It is important to note that this threshold of 18 satellites has been found to be the minimum acceptable number of satellites for high system performance. Studies

performed by the Aerospace Corporation determined that 18 satellites provide worldwide coverage (using a 10^{o} mask angle) 96.3% of the time (16).

A similiar computer model will be used to determine the optimum time interval between replenishment launches given a specific satellite design life and reliability through final orbit insertion. Optimality, as used here, refers to the longest time between launches after initial buildup that will maintain the constellation with a minimum number of satellites required for worldwide continuous coverage at least 99% of the time (13).

The model used to determine the minimum number of satellites necessary for worldwide continuous coverage was provided by the Aerospace Corporation and is known as the Efficient GPS Availability Determination (EGAD) Model. It has been modified by this analyst in order to test four different constellation configurations for coverage over various geographic locations. The model can simulate up to 30 satellites in the GPS constellation. Depending on the analysis desired, the model will evaluate specific local or global coverage over time. The model evaluates the constellation at set time intervals and reports the number of satellites available (in the field of view) continuously and overall system availability (16). The best performing constellation will be used in the satellite attrition analysis.

In the attrition analysis, satellites will be deleted from the same orbital plane, adjacent planes, and alternate planes in order to assess the immediate impact on coverage. The geographical areas to be investigated include locations in the

Far East, the Middle East, Europe, Scandinavia, the North Atlantic region, North America, Central America, South America, Africa, and Australia.

Objective

The primary objective of this research is to provide the Air Force Space Division with operational planning information, upon which GPS program managers may schedule replenishment launch events and project the size of future block buys. This study will simulate the operation of GPS over a 20 year period and will estimate the required number of satellites to maintain the system as well as the operational cost in FY 86 dollars. Finally, it is important to know which geographic areas will have degraded navigation coverage as a result of satellite attrition. This research will specify the areas most affected as well as those least affected by the loss of any satellites.

Approach and Methodology

This study uses a simulation approach to determine the satellite and system availability for a number of operable satellites. The EGAD Model has been modified to allow the user to configure the GPS constellation with any number of satellites and then test the system for continuous local or global coverage over time. As mentioned earlier, four constellations will be examined. Each constellation will be described in detail.

The first constellation (Fig. 1) is known as the Walker 18/6/2 (16). This configuration has the minimum (18) acceptable

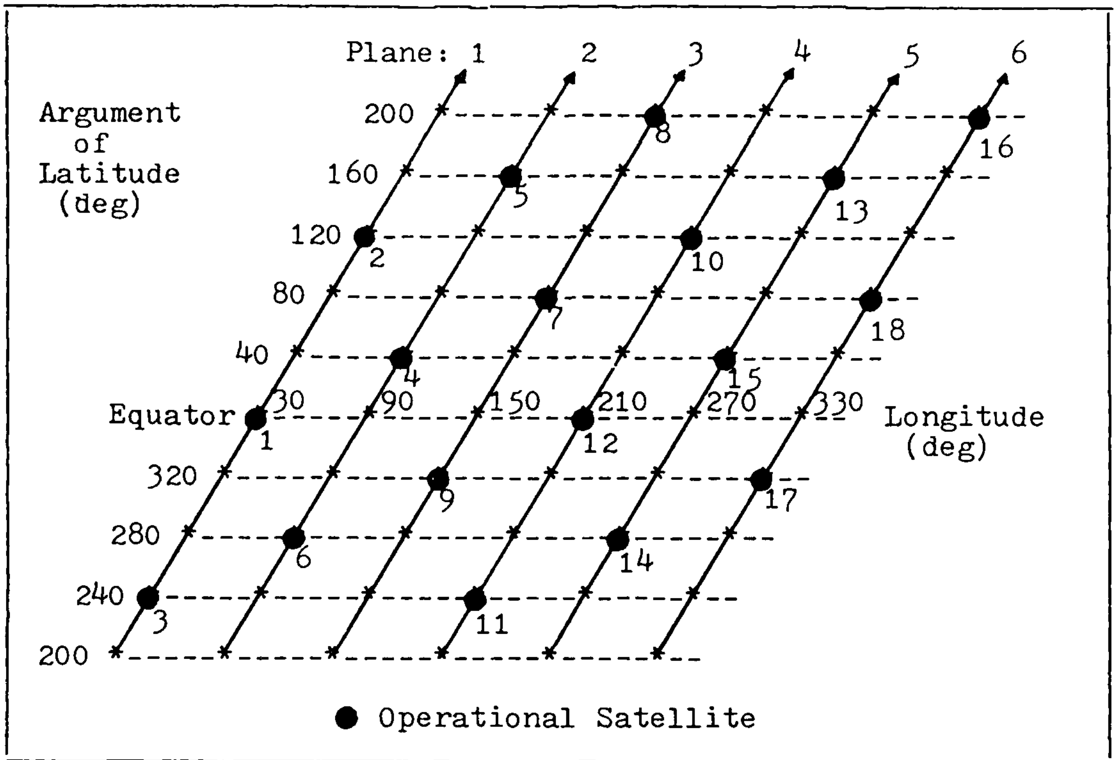


Fig. 1. Constellation: Walker 18/6/2

number of satellites for satisfactory system performance. The constellation is comprised of six orbital planes separated by 60 degrees of longitude. There are three satellites uniformly spaced in each plane with 120 degrees of separation between adjacent satellites. Plane to plane phasing is 40 degrees. Each satellite has another satellite in the plane to the east 40 degrees ahead of it in orbit.

The next configuration (Fig. 2) to be examined is the baseline recommendation of the Aerospace Corporation. It is referred to in the literature as the Walker 18/6/2 plus 3 spares (10). The difference between this constellation and the one mentioned previously is the addition of three spares in planes 1,3 and 5 respectively. Figure 2 shows the nominal position of each satel-

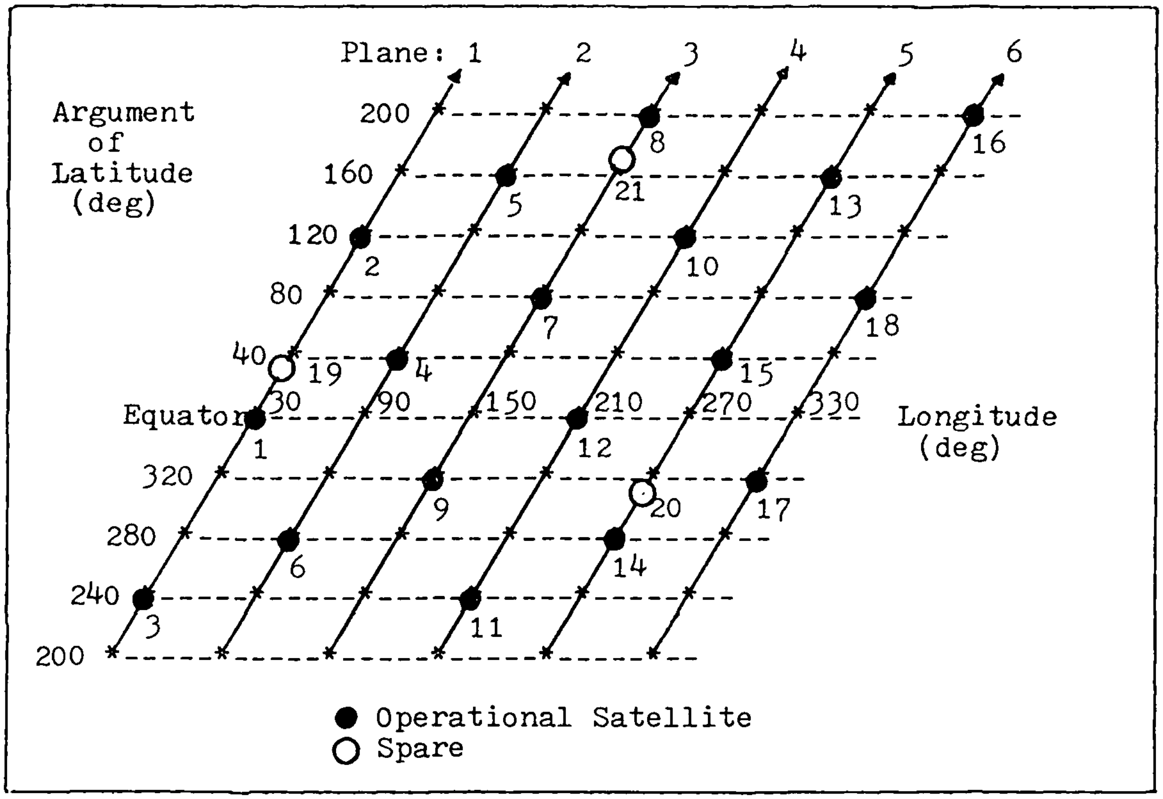


Fig. 2. Constellation: Walker 18/6/2 Plus 3 Spares

lite in the basic configuration as well as the position of each spare. Notice that the planes with four satellites do not have uniform spacing among the satellites. In plane 1, the spare is located 30 degrees ahead in latitude of the satellite at the equator. This strategy is useful since it requires less rephasing should one of the adjacent satellites fail. The spare in plane 3 is 30 degrees below the satellite located at 200 degrees latitude. The last spare is positioned 30 degrees ahead of the satellite at 280 degrees latitude. The phasing between planes is 40 degrees.

The non-uniform spacing in the planes with four satellites shows a trade-off between coverage and the time for rephasing in

the event of failure in a primary satellite. To date, studies have not been performed to see if indeed there is a loss in coverage and what that loss actually is. Therefore, the third configuration moves the spares into positions such that there is uniform spacing (90 degrees) in the planes with four satellites. Figure 3 depicts a rephased 21 satellite constellation. The planes with three satellites still maintain uniform spacing with 120 degrees between satellites. There is plane to plane phasing of 45 degrees.

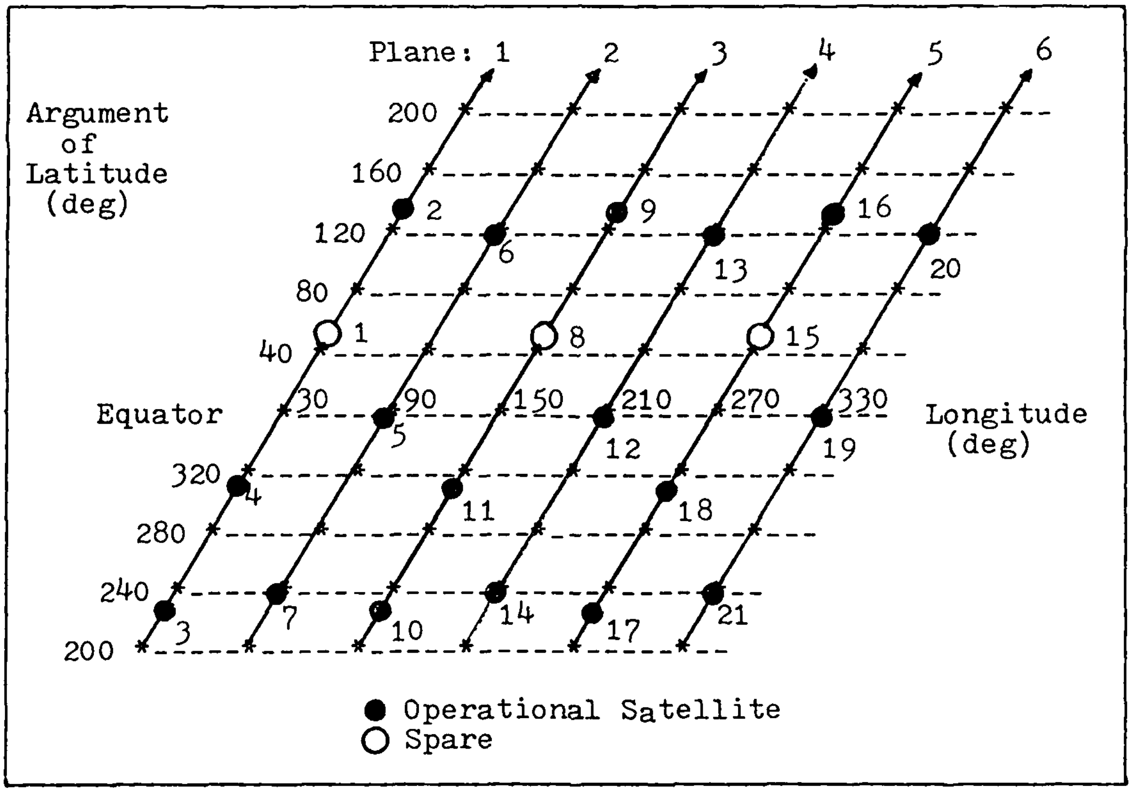


Fig. 3. Constellation: 21 Satellites, Rephased

The final configuration to be evaluated is depicted in Figure 4. This configuration is the basic Walker 18/6/2 with six spares. Notice that there is a spare in each plane, but

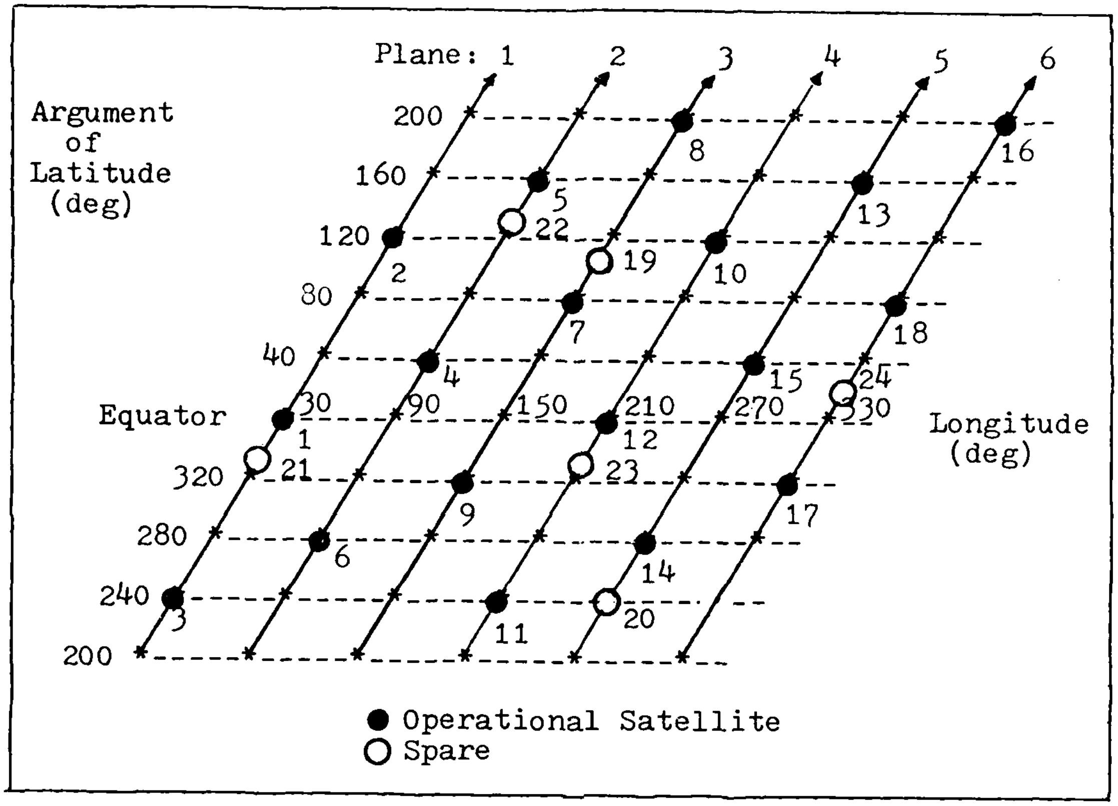


Fig. 4. Constellation: Walker 18/6/2 Plus 6 Spares

each one is positioned so that it can be quickly rephased to replace an adjacent satellite. There is 40 degree phasing plane to plane.

The FAA has expressed an interest in commercial applications of GPS (6). This would impose more stringent restrictions on the constellation selected, such as the higher mask angle (7.5 degrees) mentioned earlier (6). Prior to the FAA's involvement, constellation research used a criterion of having at least four satellites in the field of view (FOV) continuously with a minimum elevation (mask) angle of five degrees to define the FOV.

Mask angle is a measurement of the sector of sky immediately above the horizon in which the satellites are effectively invisible (5). Traversing the sky from the local horizon to zenith

defines 90 degrees of view in reference to the user. Masking can be caused by antenna placement, airframe interference, and the elevation of surrounding terrain (5). Choosing a higher mask angle lessens the time delay error due to refraction of the GPS signal. However, the primary effect of raising the mask angle is to decrease the user's FOV and therefore lower the probability of having any number of satellites available at any particular time.

Another criterion that will be used in this study is system availability. This refers to the percent of time that the geometry among the satellites in the FOV is sufficient for accurate navigation. A measure of system availability found throughout the literature is called the Position Dilution of Precision (PDOP) (9). This value is the ratio of the three-dimensional root mean squared (rms) position error to the rms ranging error from all the satellites. The PDOP is determined by the geometry of the satellite relative to the user. A PDOP value less than six is commonly used as the criteria for good navigational geometry between the user and the GPS constellation (9). Therefore, in this study, the system will be deemed available when the value of PDOP is less than six and thus 'system availability will be expressed as the percent of time that this condition occurred.

Using the criteria already established, this study will select various locations from around the world in order to find the best constellation among the four chosen for evaluation. The Aerospace Corporation provided the list in Table I. These

Table I. Cities Used to Test Global Coverage

City	Latitude	Longitude	City	Latitude	Longitude
Acalpulco, Mexico	16.51	-99.56	Honolulu, Hawaii	21.52	-157.99
Anchorage, Alaska	62.28	-149.83	Hormuz, Middle East	27.00	56.00
Ankara, Turkey	39.55	32.50	Las Palmas, Canary I.	28.08	-15.27
Brussels, Belgium	51.00	5.00	Lima, Peru	-12.06	-77.03
Buenos Aires, Argentina	-34.40	-58.30	New Hampshire, US	42.90	-71.70
Camp Parks, California	37.73	-121.88	New London, Conn.	41.40	-72.20
Calcutta, India	22.30	88.20	Pago Pago, Amer. Samoa	-14.16	-170.43
Cape Kennedy, Florida	28.28	-80.28	Panama Canal	8.95	-79.60
Cape Town, South Africa	-33.56	18.28	Riyadh, Saudi Arabia	24.39	46.46
Caracas, Venezuela	10.35	-66.56	Rome, Italy	41.82	12.25
Charleston, SC	32.48	-79.58	Seychelles, Indian O.	-4.70	55.50
Christchurch, New Zeal.	-43.33	172.40	Sydney, Australia	-34.00	151.00
Cold Lake, Canada	54.41	-110.28	Stockholm, Sweden	59.20	18.05
Diego Garcia, Indian O.	-6.34	72.24	Taipei, Taiwan	25.05	121.32
Eglin, Florida	30.64	-86.74	Tananarive, Malagasy	-18.52	47.30
Farnborough, England	51.22	-0.77	Tel Aviv, Israel	32.05	34.46
Fort Monmouth, NJ	40.03	-74.34	Thule, Greenland	76.50	-61.60
Fortuna, ND	48.90	-101.50	Tokyo, Japan	35.40	139.45
Galveston, TX	29.17	-94.48	Tromso, Norway	69.65	18.93
Grand Bahama	26.63	-78.42	Vandenberg, California	34.79	-120.51
Guam	13.60	144.90	Yuma, Arizona	33.02	-114.40

42 cities were selected because they represent a global sample of locations including every major land mass and ocean area (10). There are 18 cities that represent the equatorial latitudes between 30° South and 30° North. There are 21 cities in the mid latitudes between 30°- 60° South and 30°- 60° North. Finally, there are three cities in the far northern regions above 60° North.

The 42 cities span every continent. With most of the world's population located between the northern and southern mid latitudes, it is reasonable to evaluate coverage in the areas of maximum use. In addition to the cities listed in Table I, 37 other locations will be evaluated for continuous local coverage.

This study will examine coverage every 2.5 degrees of latitude at longitude 90° West, a longitude that passes north to south through the central portion of the United States.

Altogether, the 79 selected locations represent a sufficient sample to measure the performance of the constellations relative to one another. Each simulation will test one of the four configurations against all 79 locations and report satellite and system availability. The constellation that maintains four satellites in the FOV continuously and has a system availability of at least 99% will be recommended as the baseline configuration for GPS.

Besides the EGAD model, the Aerospace Corporation has two models which enhance GPS procurement management. The models are used in planning the production and launch phases for the GPS program. The two models are very important since they

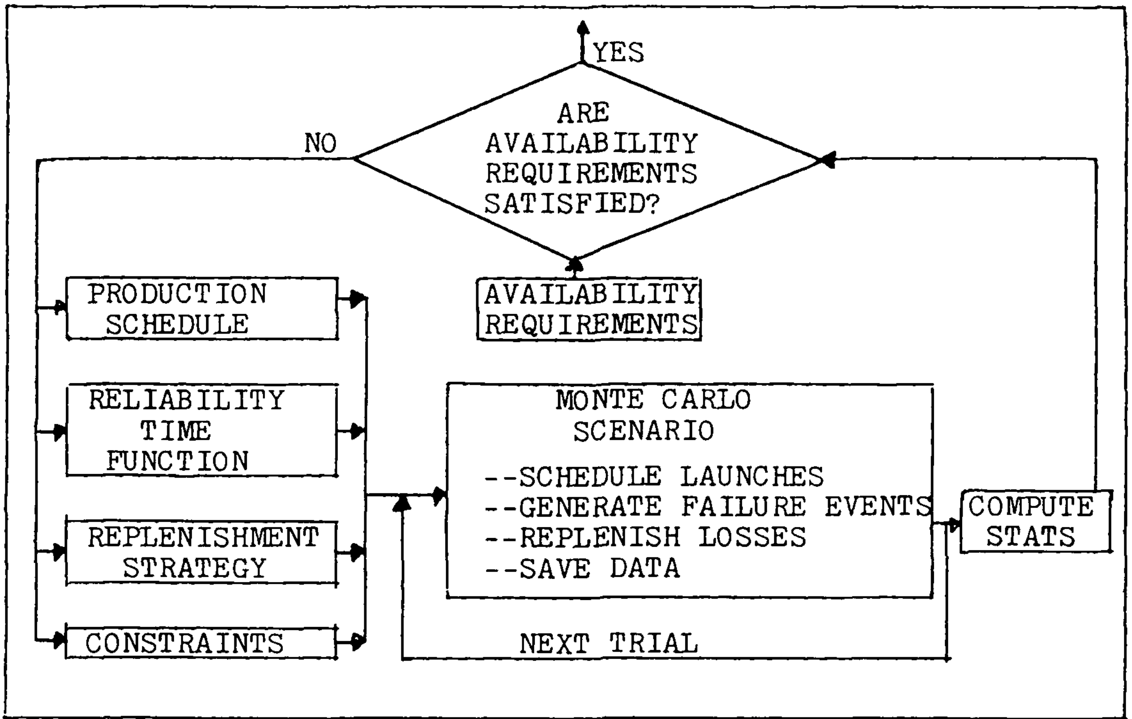


Fig. 5. The Aerospace Corporation GAP Analysis

were developed explicitly to handle a high cost acquisition process involving a situation with the following characteristics.

- -- High cost per satellite ($42 Million, FY 86)
- -- 50,000-100,000 parts
- -- Multiple payloads/Shared subsystems
- -- Dormancy of satellites is a consideration
- -- Very high engineering/production restart-up costs
- -- Overpurchasing is not viable
- -- Underpurchasing can lead to weakening of National Defense
- -- Extension in design life saves tremendous money

The first model (Fig. 5), known as the 'GAP' or Generalized Availability Program, is a monte carlo event-time simulation. Basically, GAP determines a satellite launch schedule based on a given production schedule and a desired level of operational satellites required.

There are four major inputs to GAP. The production schedule

is the time of delivery for GPS satellites to the system integration facility. The reliability time function is a probability distribution function that schedules a failure event based on the estimated design life of each satellite. The replenishment strategy is based on a decision to launch or cancel a launch depending on the status of the constellation. Other constraints include the reliability through final orbit insertion.

There is one qualification that needs to be made at this point. The Aerospace Corporation uses the concept of availability in several ways (7). In the general sense, availability is described as the probability that a minimum requirement is met. For the GAP model, this would mean a minimum number of satellites are in orbit. In the EGAD model, system availability refers to the percent of time that PDOP was less than six.

Referring back to the diagram in Figure 5, the main program schedules launches, generates failure events, and launches replenishment satellites based on a given strategy. Statistics are computed and if the availability requirements are satisfied (i.e., a minimum number of functional satellites) the model completes the simulation. If availability requirements are not met, then the replenishment strategy is modified until the availability requirements are satisfied. This is an iterative process that may require many simulations.

The GAP model projects 10 months ahead. If fewer than 21 satellites are expected, the mission is not cancelled. The

model then calculates the probability that not all of the 18 basic positions in the Walker 18/6/2 constellation will be filled and if this probability is acceptable to GPS program managers, the launch is cancelled.

The second model that the Aerospace Corporation uses is the Reliability Network Analyzer Model or 'RNA' (7). According to consultants at Aerospace, RNA provides an advanced systematic approach to satellite reliability analysis, modeling and prediction (7). This model takes the threshold availability or required number of satellites in the constellation, the maintenance number of satellites and a reliability time function and then calculates a fixed launch schedule for GPS. The model incorporates the following constraints imposed by NASA (7).

-- All GPS launches will be fixed launches
-- Cancelling decision made 10 months prior to launch
-- Satellite destination determined 2 months prior to launch

The Q-GERT model developed in this study takes a different approach from the two models discussed earlier. The objective is to maintain a given number of functional satellites. This criteria will be referred to as 'point availability' or the fraction of the threshold number and is a value between 0.00 and 1.00.

The approach used will be a simulation model that determines the optimum time interval between launches to maintain the threshold number of satellites 99% of the time. Satellite design life will be varied from 7.5 years to 15.0 years and reliability through final orbit insertion will range from 90-98%. Output

from this model will include the following.

- -- Plots of TIME versus SATELLITES AVAILABLE and TIME versus PERCENT(POINT) AVAILABILITY
- -- Number of satellites required over 20 years
- -- Operating cost over 20 years in FY 86 dollars

The Q-GERT model developed in this study is known as the Replenishment Launch Strategy Model. It is also a monte carlo event-time simulation that determines a fixed replenishment launch schedule for GPS. There are several differences between this model and those used by the Aerospace Corporation. First, there is no decision to cancel a future launch in the Q-GERT model. Next, the Aerospace model uses a criteria of 98% availability of 18 satellites, while this model determines a strategy to maintain a given threshold number (in this case, 21 satellites) 99% of the time. The last major difference is in the initial buildup rate. The Aerospace Corporation uses an initial buildup rate of eight to nine launches a year. This figure relies on having an ideal NASA manifest (i.e., being able to launch on every mission manifested) (16). The Q-GERT model uses a less optimistic initial buildup rate of seven launches per year for the first three years. Afterwards, the model determines an optimum launch rate to maintain a certain threshold number of satellites in the constellation.

A detailed analysis of the Aerospace Corporation's EGAD model and a discussion of the Replenishment Launch Strategy Model are provided in chapters 2 and 3 respectively. An in-depth analysis of the performance of both these models will follow in Chapter 4. Finally, Chapter 5 recaps the research

performed in this report and presents a summary of conclusions and recommendations. The appendices contain the program listing of the Q-GERT model as well as satellite and point availability curves for all the simulations used in this report.

II. The Aerospace Corporation EGAD Model

Purpose

The primary purpose of the Efficient GPS Availability Determination Model is to enable operations analysts to simulate the GPS constellation(16). By modifying the configuration and number of satellites, one can determine the system's performance with regard to worldwide coverage. In addition, the program allows users to evaluate coverage over a specific geographical area. Another major attribute of EGAD is its ability to assess the impact on worldwide coverage given the attrition of several satellites.

Design

The EGAD model is a complex, yet flexible program consisting of a main program segment with numerous ancillary modules. The program is well documented with descriptions and definitions of the significant variables throughout the program. An overview of the main program algorithm is provided on the next page (Fig. 6).

The original program has been modified by this analyst to concentrate on a few key areas. Specifically, the entire data initialization code was restructured to allow the user to focus on changes to configuration and number of satellites to be deleted in the attrition analysis. Conversion was made from the IBM 3033 FORTRAN 66 with extensions to the CYBER's FORTRAN 5 programming language. This involved changing to compatible intrinsics and modifying several subroutines.

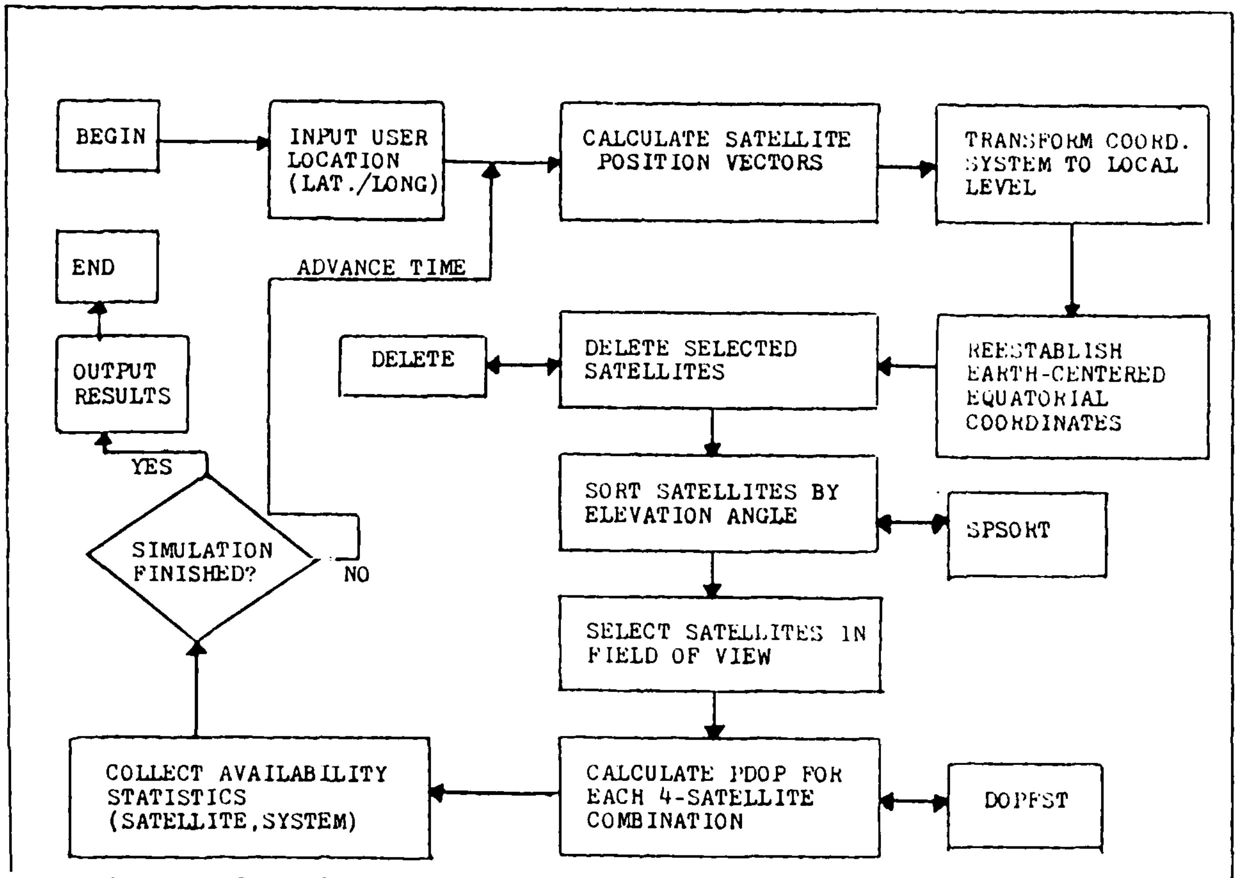


Fig. 6. Overview of the EGAD Main Program Algorithm

The model is set up to be run in batch mode. All variables are set to default values in the main program segment except for the constellation configuration which must be changed for each run involving a different constellation. When the program is executed, the program requests the user's coordinates and then evaluates the system over an eight hour period at 20 minute intervals.

Referring back to the main program overview (Fig. 6), the model requests the coordinates of the user's location in degrees of latitude and longitude. Latitude is expressed as a positive value for northern latitudes; a negative value is used for southern latitudes. East longitude is expressed as a positive value between 0^{o} and 180^{o}. West longitude is expressed as a negative value between 0^{o} and -180^{o}.

Next, the time loop is started using 20 minute increments. The position vector for each satellite is calculated and expressed in earth-centered equatorial IJK coordinates (X,Y,Z) where Z is North. A matrix transformation converts the (X,Y,Z) coordinates to a local level coordinate system where X is East and Y is North.

The model uses another matrix transformation to reestablish the earth-centered equatorial satellite position coordinates. A final transformation converts satellite position to earth surface local level coordinates centered at the ground point specified by the user's location.

Subroutine DELETE is called if there are any satellites to be deleted in the current simulation. The subroutine deletes satellites by changing the satellite's calculated elevation angle

to -89 degrees. By doing this, the satellite is not selected as one above the 7.5 degree mask angle that defines the FOV.

Subroutine SPSORT is called to sort all of the constellation satellites by elevation angle. The model then selects the satellites in the FOV and discards any satellites with elevation angles below 7.5 degrees.

The program now calls Subroutine DOPFST which calculates the PDOP for every 4-satellite combination in the FOV. It continues to evaluate the combinations until a PDOP less than six is found. For each time increment that the PDOP was less than six, the system availability counter is increased in Subroutine COLLEC. At the end of the simulation, this system availability is printed out along with the number of satellites in the FOV continuously.

The program can now be used to evaluate coverage at various locations for the four different constellation configurations. This is sufficient to judge the performance of each relative to one another. The primary benefit of this approach is to allow some user interaction and yet minimize the model's processing time in lieu of having global coverage evaluated over some 12,000 locations.

The overview only lists a few of the support modules available as these were the primary ones needed for this research. However, it is useful to describe the other modules and review their specific functions.

In the list that follows, each module is shown with its program name and a description of its purpose and function.

Support Modules

Module	Purpose and Function
SELECT	Selects grid points for plotting histogram.
ORBSTR	Initializes orbital element parameters and satellite positions.
DELETE	Deletes selected satellites.
SPSORT	Sorts satellites in order of descending elevation angle. Saves only those in FOV.
SORT	General sort routine to sort any array.
NAVFND	Collects navigation data on satellite combinations.
DOPFST	Calculates Dilution of Precision (DOP) and ends upon finding first DOP below threshold.
DOPFND	Calculates the best DOP for system.
COUNTS	Calculates system value for basic constellation and up to one spare.
COUNT2	Finds instantaneous probability of GPS availability for 1-2 satellite outages.
COUNT4	Same as COUNT2 for 1-4 satellite outages.
COUNT8	Same as COUNT2 for 1-8 satellite outages.
COLLEC	Collects histogram data.
FINAL	Computes system value for satellite outages.

The SELECT module chooses user locations for analysis based on a minimum/maximum latitude and longitude. For example, suppose one wished to analyze coverage in the northern hemisphere for every 5 degrees of latitude and every 30 degrees of longitude. In this case, there would be 228 locations evaluated ($90^\circ/ 5^\circ +$ Equator = 19 latitudes; $360^\circ/ 30^\circ = 12$ longitudes; total locations

are 19 x 12 = 228).

The primary function of the ORBSTR module is to initialize the parameters related to the input orbital elements that are used to compute the satellite positions.

The SORT module is a general algorithm that sorts an array of elements in an increasing or decreasing order depending on the user's preference.

The NAVFND module evaluates each 4-satellite combination in the FOV and calculates the navigation error (standard error probable) in meters. This subroutine may be used in lieu of DOPFST which computes PDOP for each combination.

The COUNTS module accumulates data for computing the system value (percent of time with PDOP less than six) for the basic 18 satellite constellation. If a PDOP less than six is not found, the module adds a spare to the constellation and repeats the process.

The COUNT2, COUNT4, and COUNT8 modules calculate the instantaneous probability of system availability given up to eight satellite outages. Each routine stores the average system value for each outage scenario. A summary of the results is generated by the FINAL module.

The EGAD model simulates a system of N satellites placed in circular orbits at an altitude of 10,898 nautical miles and a period of nearly 12 hours. The inclination of each satellite is 55 degrees. Table II shows the initial positions for each satellite in its specific constellation.

Table II. Initial Satellite Positions for Constellations

Walker 18/6/2 Sat.	RA,AN*	Lat.	Walker 18/6/2+3 Sat.	RA,AN	Lat.	21 Satellites (R)* Sat.	RA,AN	Lat.	Walker 18/6/2+6 Sat.	RA,AN	Lat.
1	30°	0°	1	30°	0°	1	30°	45°	1	30°	0°
2	30	120	2	30	120	2	30	135	2	30	120
3	30	240	3	30	240	3	30	225	3	30	240
4	90	40	4	90	40	4	30	315	4	90	40
5	90	160	5	90	160	5	90	0	5	90	160
6	90	280	6	90	280	6	90	120	6	90	280
7	150	80	7	150	80	7	90	240	7	150	80
8	150	200	8	150	200	8	150	45	8	150	200
9	150	320	9	150	320	9	150	135	9	150	320
10	210	120	10	210	120	10	150	225	10	210	120
11	210	240	11	210	240	11	150	315	11	210	240
12	210	0	12	210	0	12	210	0	12	210	0
13	270	160	13	270	160	13	210	120	13	270	160
14	270	280	14	270	280	14	210	240	14	270	280
15	270	40	15	270	40	15	270	45	15	270	40
16	330	200	16	330	200	16	270	135	16	330	200
17	330	320	17	330	320	17	270	225	17	330	320
18	330	80	18	330	80	18	270	315	18	330	80
			19	30	30	19	330	0	19	150	110
			20	270	310	20	330	120	20	270	240
			21	150	170	21	330	240	21	30	330
									22	90	130
									23	210	330
									24	330	20

*RA,AN = Right Ascension(longitude) of the Ascending Node; (R) = Rephased

In order to make use of the EGAD Model in as uncomplicated manner as possible, the program was modified to only request the user's latitude and longitude for any particular simulation. All other variables are set to initial values through the use of Data statements in the main program segment. The significant variables in the simulations run for this study are elevation angle and the time coverage. For this study, an elevation angle of 7.5 degrees defines the FOV and the model will simulate eight hours of operation. While one does not get a complete replication of the system in less than 12 hours, eight hours is sufficient to judge the four configurations relative to one another.

As mentioned earlier, the primary output from EGAD is the total number of satellites available over time as well as the percent of time the system was available. This study will select the configuration that has at least four satellites in the FOV continuously and system availability of 99%. The number of satellites in this configuration will be the critical design constraint for the Replenishment Launch Strategy Model which is discussed in the next chapter.

III. The Replenishment Launch Strategy Model

Purpose

The Replenishment Launch Strategy Model is designed to simulate the operations phase of GPS over 20 years. The basic events that are modeled include launch, a Low-Earth-Orbit (LEO) storage capability, Upper Stage boost, orbital plane selection, operation and termination. Another primary objective is to determine the optimum time interval between replenishment launches that will maintain the required number of satellites in the constellation. Finally, operational cost data will be accumulated for 20 years of operation.

Design

The design of this model is structured around the events it is simulating. A GPS satellite is launched by the Shuttle into LEO. From LEO, the satellite is boosted into its selected orbital destination by the Upper Stage. Once in the constellation, the satellite operates until termination.

There are several major assumptions made in this model. First, it is assumed that a production schedule exists and is sufficient to meet the scheduled launches. Next, the order in which the basic constellation positions are filled during the buildup phase is not taken into account. During the replenishment phase, however, the satellites are launched into the plane with the fewest satellites. Another assumption is that the GPS satellites have a design life of 7.5 years (16). Reliability rates for the Shuttle, the Upper Stage and Apogee Kick Motor

are estimated by Space Division to be 98%, 97% and 99% respectively and are independent of each other (16). Each reliability value is independent because each event involves a separate system with no overlap of activity. In order to get combined probability for the events through final orbit insertion, the three independent reliability rates are multiplied together to get a 94% for the simulation's boost event. Hence, any future reference to reliability through final orbit insertion will in fact be a combined reliability as it was just described.

A total of 61 runs will be made for each simulation. According to Shannon (15), if a normal distribution is assumed, then this number is sufficient to insure a 95% confidence that the sample mean of the statistic being collected is within $\frac{1}{4}$ standard deviation of the true mean. Conversations with the Aerospace Corporation's consultants on GPS reliability studies confirm that the assumption of normalcy is valid (7). Consequently, the reported results of this study will be average values that are close estimates of the true values. For example, the model reports the number of operating satellites for each month. The average over 61 runs is then calculated for each month and the result printed out to a histogram file. The figures for operational cost and number of satellites required over 20 years are calculated in the same manner.

This study uses 15 different runs of 61 simulations each to measure the performance of the system given various combinations of design life and reliability through final orbit insertion. The basic idea is to hold design life and reliability

through final orbit insertion constant while varying the time interval between replenishment launches to find the optimum interval that maintains N satellites 99% of the time.

The first 15 runs involve values of satellite design life from 7.5 to 15.0 years and a range in reliability through final orbit insertion of 90% to 98%. To reiterate, the baseline estimates for satellite design life is 7.5 years with a 94% reliability through final orbit insertion. The basic strategy in each of the 15 runs is to launch seven satellites per year during the first 36 months and thereafter find the optimum time interval between launches to maintain the system at a designated threshold number.

The final 12 runs are used to estimate when the current block buy of 28 satellites will need to be replenished. Once all 28 satellites have been launched, no further launches are allowed and statistics are collected on the number of functional satellites operating each month.

The Replenishment Launch Strategy Model is written in the Q-GERT programming language. A diagram of the model is provided in Figure 7 with the actual program listing provided in Appendix A. Each component in the network will be discussed in sequence.

Source Node 10 schedules GPS launches and assigns a failure time to each satellite launched. The failure time is selected from a Normal distribution (mean = 90 months, standard deviation = 12 months) and stored in Attribute 1 (7).

Queue Node 20 represents a LEO storage capability for GPS satellites after launch. In LEO, the satellites will experience

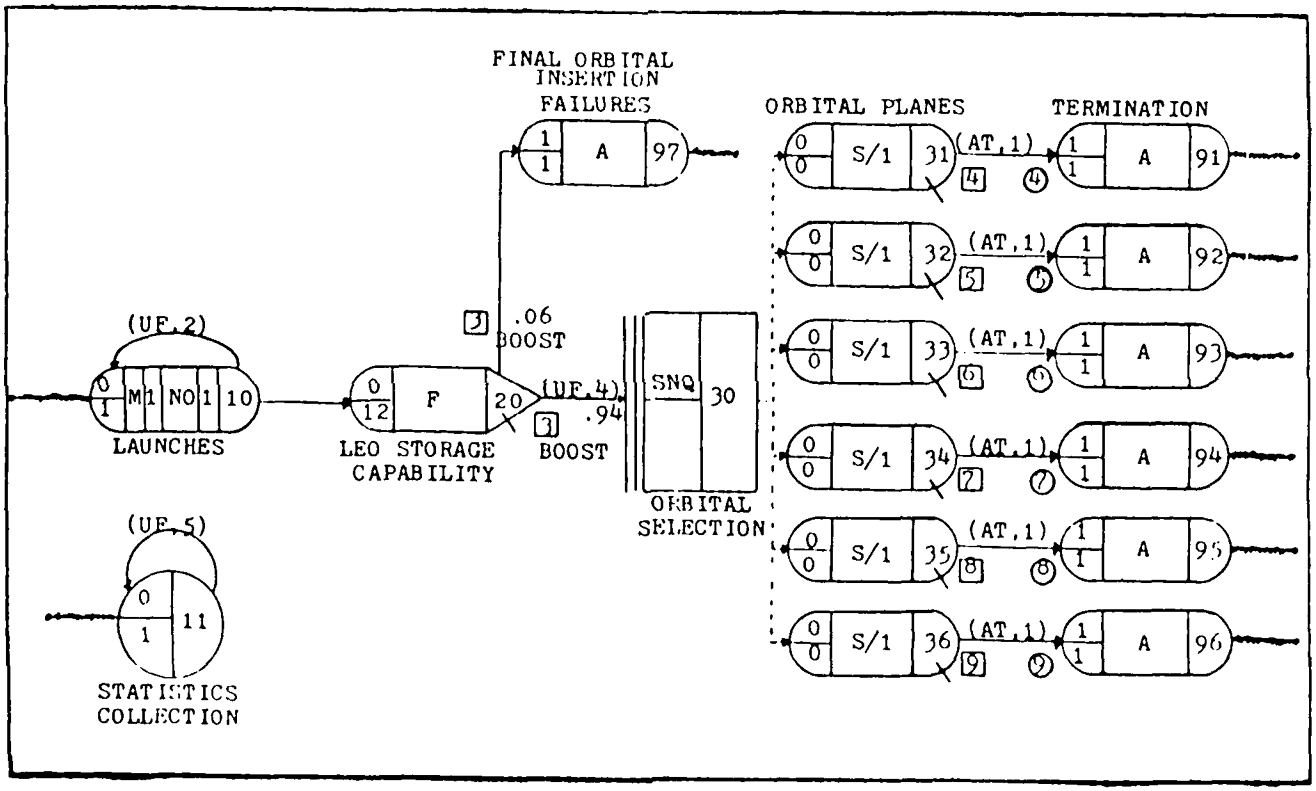


Fig. 7. Q-GERT Network for the Replenishment Launch Strategy Model

nodal regression of 7 degrees per day, and within 27 days could reach any desired orbital plane. The model uses a time period of one month from Shuttle deployment to final placement in the constellation.

Activity 3 models the boost phase of the GPS launch from LEO into final position in the constellation. Recall that this event includes the deployment from the Shuttle, the Upper Stage firing and the firing of the Apogee Kick Motor. An initial combined reliability for these three events is 94%. Once these events have occurred, the time to failure is adjusted for time spent at LEO.

Sink Node 97 represents the termination event for a satellite which failed to achieve final orbit insertion.

Selection Node 30 is a representation of orbit selection for satellites. The node selects the first available plane that has had a satellite terminate, and routes its replacement to that plane. Blocking is permitted since it is desired that only a maximum of four satellites can be in any one plane.

Queue Nodes 31-36 model each of the six orbital planes. Satellites are placed into the operation activity based on the shortest time to failure. The queues do not allow waiting and the satellite is routed only if the activity is free.

Activities 4-9 are the operation event for each orbital plane. There are a maximum of 24 servers at any time and satellites remain in the activity until failure. Note that the scheduled failure time is carried in Attribute 1.

Sink Nodes 91-96 are the termination events for GPS satellites. As the satellites terminate, subsequent satellites

take their p[illegible]e.

There are three User Functions used in the Q-GERT model to enhance the simulation. User Function 2 schedules the launches according to each strategy. It sets the time interval between launches at 1.7 months for the first 36 months (7 satellites per year) and then as required by each simulation for the remainder of the 20 years. User Function 4 adjusts the value carried in Attribute 1 (time to failure) for the time spent in LEO. User Function 5 collects the statistics for the model. Specifically, it stores the average value of the number of operating satellites at each month, the average system availability (percent of time with 21 satellites operating) and the operating cost in billions based on FY 86 dollars. A figure of $74 Million per satellite is used in this study ($42 Million per satellite, $6 Million per Upper Stage and a $26 Million per satellite Shuttle fee).

For each simulation, a User Function is called at the end of the 61st run and statistics are computed for the average number of satellites required for 20 years operation. This number is then the minimum number of satellites required to maintain the threshold number of satellites designated by the EGAD model. The average total operating cost and average percentage of time that the threshold was maintained is also computed.

IV. Analysis of Models

The Aerospace Corporation EGAD Model

The primary objective in testing four constellations for coverage was to determine the minimum number of satellites needed as well as the best configuration for the constellation. The performance criteria for judging each constellation was set at maintaining four satellites in the FOV continuously and an average system availability of 99%. Each constellation would be tested against the 79 selected locations for local and global coverage. If each constellation performs well, then it will be tested for average system availability (percent of time with PDOP less than six). The combined performance will provide a ranking among the constellations and the one chosen will have the best coverage and average system availability for the number of satellites.

The results of the global and local coverage analysis are provided in Table III and IV respectively. In Table III, one can see that all of the configurations meet the established criteria of having four satellites in the FOV continuously. Of the candidates, the Walker 18/6/2+3 configuration had excellent coverage for the number of satellites with an average of 5.17 satellites in the FOV continuously. The rephased 21 satellite constellation was slightly worse with 4.93 satellites followed by the basic Walker 18/6/2 with 4.57 satellites.

One should notice the areas of minimum coverage (only four satellites visible) in Table III. Most of the cities where only

Table III. Maximum Number of Satellites in FOV, Global Coverage

City	Walker 18/6/2	Walker 18/6/2+3	21 Satellites Rephased	Walker 18/6/2+6
Acapulco	5	5	5	7
Anchorage	4	5	5	6
Ankara	4	4	4	5
Brussels	4	5	5	6
Buenos Aires	5	5	4	6
Camp Parks	4	4	4	6
Calcutta	5	6	5	5
Cape Kennedy	4	5	5	6
Cape Town	4	5	5	5
Caracas	5	6	6	8
Charleston	4	5	4	6
Christchurch	4	4	5	4
Cold Lake	5	5	5	6
Diego Garcia	5	6	6	7
Eglin	5	6	5	7
Farnborough	4	5	5	6
Fort Monmouth	4	5	5	6
Fortuna	5	5	5	6
Galveston	5	5	4	7
Grand Bahama	5	6	5	7
Guam	5	6	6	6
Honolulu	5	5	5	6
Hormuz	4	5	5	6
Las Palmas	5	5	5	6
Lima	5	7	5	7
New Hampshire	4	5	5	6
New London	4	5	5	6
Pago Pago	5	5	5	5
Panama	5	6	6	8
Riyadh	5	5	5	6
Rome	4	5	5	5
Seychelles	5	6	6	6
Sydney	4	4	4	5
Stockholm	4	5	5	6
Taipei	5	6	5	5
Tananarive	5	5	5	6
Tel Aviv	4	4	4	6
Thule	6	6	6	7
Tokyo	4	5	4	6
Tromso	5	6	6	7
Vandenberg	4	4	4	6
Yuma	5	5	4	7
Averages	4.57	5.17	4.93	6.10

four satellites are available are at mid latitudes in the northern and southern hemispheres. For many of the cities with only four satellites available, the system availability was less than 99%. What these results indicate are that temporary outages will occur at the mid latitudes. This has been reported in studies at the Aerospace Corporation which map these outages for global coverage (13). These outages last approximately 10 minutes and with backup navigational equipment (inertial navigation), there would be little adverse effect on a mission.

The evaluation of local coverage showed that the rephased 21 satellite constellation performed better than the recommended Walker 18/6/2+3 with an average of 5.35 satellites versus 5.16. However, in the mid latitudes (30^{o}- 50^{o}North), the rephased configuration barely met the criteria of four satellites and in many cases the system availability was well below 99%. In Table IV, one can observe that the Walker 18/6/2+3 has the more consistent coverage of the two 21-satellite constellations. Finally, if the budget would allow 24 satellites, the coverage provided by the Walker 18/6/2+6 was greatly improved with an average of 6.10 satellites for the cities and 6.32 satellites for local coverage.

A summary of the coverage analysis is provided. Clearly, the results indicate that the Walker 18/6/2+3 is the most consistent performer overall for the number of satellites.

Table IV. Maximum Number of Satellites in FOV, Local Coverage

Longitude 90W Latitude	Walker 18/6/2	Walker 18/6/2+3	21 Satellites Rephased	Walker 18/6/2+6
0.0°	5	6	6	8
2.5	5	6	6	8
5.0	5	6	6	8
7.5	5	6	6	7
10.0	5	6	6	7
12.5	5	6	6	7
15.0	4	5	6	7
17.5	5	5	6	7
20.0	4	5	5	7
22.5	5	5	5	7
25.0	4	5	5	7
27.5	5	5	5	7
30.0	5	5	4	7
32.5	5	5	4	6
35.0	4	4	4	6
37.5	5	5	4	6
40.0	5	5	4	6
42.5	5	5	4	6
45.0	5	5	4	6
47.5	5	5	4	6
50.0	5	5	5	6
52.5	4	4	5	6
55.0	5	5	5	7
57.5	4	4	5	6
60.0	4	4	6	5
62.5	4	4	6	5
65.0	4	4	6	5
67.5	4	5	6	6
70.0	4	5	6	6
72.5	5	5	6	6
75.0	5	5	6	6
77.5	5	6	6	7
80.0	6	6	6	7
82.5	6	6	6	7
85.0	6	6	6	7
87.5	6	6	6	7
90.0	6	6	6	7
Averages	4.84	5.16	5.35	6.54

Constellation	Average Number of Satellites in FOV Global Coverage	Local Coverage	Combined
Walker 18/6/2	4.57	4.84	4.70
Walker 18/6/2+3	5.17	5.16	5.17
21 Satellites, Rephased	4.93	5.35	5.14
Walker 18/6/2+6	6.10	6.54	6.32

While the Walker 18/6/2+3 configuration had the best combined average number of satellites available for the number of satellites in the constellation, this in itself does not guarantee high system availability. All of the constellations were tested for system availability. The results indicate that the basic Walker 18/6/2 had an average system availability of 98.84. This is consistent with results from Aerospace (16) that sytem availability for worldwide coverage (entire globe sampled) was 96.31 using a 10° mask angle. Since the FOV is smaller with the higher mask angle, it should be slightly lower than the system availability calculated using a 7.5° mask angle.

Since the system availability criteria established in this report was 99%, the 18 satellite constellation does not quite meet the requirements to be the design constraint for the Replenishment Launch Strategy model. However, the Walker 18/6/2+3 had a very high system availability at 99.33%. Adding three more spares to the 21 satellite constellation (Walker 18/6/2+6) had an average system availability of 100%. Therefore, the results support a determination that the threshold number of satellites to be maintained is 21 and this value will be the critical design constraint for the Replenishment Launch Strategy model.

The Replenishment Launch Strategy Model

The analysis of launch strategy was divided into two areas. The first 15 runs were used to test a launch strategy using replenishment under various values of satellite design life and reliability through final orbit insertion. The last 12 runs were used to test launch strategy without replenishment beyond the original 28 satellites in order to determine how long the system will maintain a given threshold number of satellites. The simulations used are listed in Table V with selected values of design life and reliability through final orbit insertion.

Table V. Simulations Used for Analysis

Simulation	Replenishment (Yes/No)	Design Life	Final Orbit Insertion Reliability
1	Yes	7.5 years	.98
2	Yes	7.5 years	.96
3	Yes	7.5 years	.94
4	Yes	7.5 years	.92
5	Yes	7.5 years	.90
6	Yes	10.0 years	.98
7	Yes	10.0 years	.96
8	Yes	10.0 years	.94
9	Yes	10.0 years	.92
10	Yes	10.0 years	.90
11	Yes	15.0 years	.98
12	Yes	15.0 years	.96
13	Yes	15.0 years	.94
14	Yes	15.0 years	.92
15	Yes	15.0 years	.90
16	No	7.5 years	.98
17	No	7.5 years	.96
18	No	7.5 years	.94
19	No	7.5 years	.92
20	No	10.0 years	.98
21	No	10.0 years	.96
22	No	10.0 years	.94
23	No	10.0 years	.92
24	No	15.0 years	.98
25	No	15.0 years	.96
26	No	15.0 years	.94
27	No	15.0 years	.92

In the first analysis, a threshold of 21 satellites was set as the performance criteria. The parameters of satellite design life and reliability through final orbit insertion were held constant while the time interval between launches was optimized. In each run, the model determined the optimum time interval between launches that maintained the system at the threshold 99% of the time whenever possible. The results of the analysis are summarized in Table VI.

Table VI. Sensitivity Analysis Results for Simulations 1-15

Satellite Design Life (Years)	Reliability Through Final Orbit Insertion 90%	92%	94%	96%	98%
7.5	3.5months .97PA* 80 sats. $5.92B	3.7months .99PA 77 sats. $5.70B	3.9months .99PA 74 sats. $5.48B	4.0months .99PA 73 sats. $5.40B	4.1months 1.00PA 72 sats. $5.34B
10.0	3.5months .97PA 80 sats. $5.92B	5.2months .99PA 61 sats. $4.51B	5.3months .99PA 61 sats. $4.51B	5.5months .99PA 59 sats. $4.37B	5.6months 1.00PA 59 sats. $4.37B
15.0	3.5months .97PA 80 sats. $5.92B	6.9months .99PA 52 sats. $3.85B	7.5months .99PA 50 sats. $3.70B	7.9months .99PA 48 sats. $3.55B	7.9months .99PA 48 sats. $3.55B

* PA = Point Availability

A description of the numbers in Table VI follows. The first value is the optimum time interval in months between replenishment launches. The second value is the point availability or fraction of time that there were 21 functional satellites in the constellation. The third value is the total number of satellites required over 20 years. The last value

corresponds to the total operating cost in billions of FY 86 dollars to maintain the system over 20 years.

One can readily see that it was not possible to obtain a point availability of .99 when the reliability through final orbit insertion was held at 90%. Therefore, an arbitrary maximum of 80 satellites was established resulting in a point availability of .97.

Table VI also shows the tremendous savings available if the reliability through final orbit insertion is increased as well as an increase in satellite design life. The current estimates for the parameters of satellite design life and reliability are 7.5 years and 94% respectively (16). Using the table, the optimum time interval between launches is 3.9 months. The system is maintained at the threshold of 21 satellites 99% of the time over 20 years.

It is important to project the savings by moving to the right and downward in Table VI. By increasing the final orbit insertion reliability from 94% to 98%, there is a savings of $140 Million. Similiarly, moving downward in the table to an increased design life of 10.0 years would save $970 Million. For a change to a 15.0 year design life, there is a $1.78 Billion savings. The results clearly indicate that it may benefit Space Division to underwrite a cost benefit analysis of the added cost in extending the design life specification for GPS to 10.0 or 15.0 years. Obviously, if the cost is less than the projected savings, then the opportunity to save budget dollars should be taken.

Another concern of this study is to project the average time a satellite will be held in LEO storage. Operationally, it is imperative that the number of satellites in this status and the time spent there be kept to a minimum. The results for simulations 1-15 are summarized in Table VII. For the baseline case of 7.5 years design life and reliability through final orbit insertion of 94%, there was an average of 1.2 satellites in LEO with a four month time delay. This is operationally feasible.

Table VII. Statistics on Satellites in LEO Storage

Simulation	Design Life	Average Number Mean	Average Number Std. Dev.	Average Time(months) Mean	Average Time(months) Std. Dev.
1	7.5 years	1.3	.24	4.4	.80
2	7.5 years	1.3	.35	4.1	1.15
3	7.5 years	1.2	.42	4.0	1.37
4	7.5 years	1.3	.49	4.1	1.54
5	7.5 years	1.5	.56	4.5	1.67
6	10.0 years	2.2	.35	9.1	1.45
7	10.0 years	2.1	.47	8.5	1.91
8	10.0 years	2.1	.40	8.1	1.60
9	10.0 years	2.0	.48	7.9	1.90
10	10.0 years	4.6	.62	14.6	1.85
11	15.0 years	4.3	.30	22.3	1.91
12	15.0 years	4.2	.40	21.7	2.35
13	15.0 years	4.1	.55	20.5	3.08
14	15.0 years	4.2	.49	20.8	2.73
15	15.0 years	6.6	.40	27.5	2.08

As one can see from the results listed in Table VII, as design life increases, the average time in LEO increases rapidly. Perhaps it would be prudent to reevaluate the fixed launch schedule once it becomes apparent that the design life is above 10 years. In that case, it would be operationally feasible to cancel a scheduled launch if there were two satellites in LEO.

Simulations 16-27 were used to determine how long the original block buy of 28 satellites would last while maintaining a minimum of 18 functional satellites in the constellation. The results are summarized in Table VIII below.

Table VIII. Satellite Percent(Point) Availability, Runs 16-27

Simulation	Design Life	Fraction of Time with N Satellites 18	19	20	21	22	23	24
16	7.5 yrs.	.26	.24	.22	.21	.18	.14	.04
17	7.5 yrs.	.26	.24	.23	.21	.18	.13	.00
18	7.5 yrs.	.26	.23	.22	.19	.16	.12	.00
19	7.5 yrs.	.25	.23	.21	.19	.15	.12	.00
20	10.0 yrs.	.41	.38	.37	.35	.32	.27	.16
21	10.0 yrs.	.41	.38	.37	.35	.32	.25	.11
22	10.0 yrs.	.40	.38	.36	.33	.28	.25	.00
23	10.0 yrs.	.39	.37	.35	.32	.28	.25	.00
24	15.0 yrs.	.71	.68	.66	.65	.60	.55	.41
25	15.0 yrs.	.71	.68	.67	.65	.61	.52	.36
26	15.0 yrs.	.70	.67	.66	.61	.56	.52	.00
27	15.0 yrs.	.69	.67	.65	.61	.56	.51	.00

The most important information from these simulations is the time when the constellation falls below 18 functional satellites. This time will determine the start of the replenishment phase for the original block buy. For the baseline case of 7.5 year design life and 94% reliability through final orbit insertion, the system maintained at least 18 functional satellites for 85 months. This would mean that the new block buy should be completed in time to meet a launch date in the fall of 1993.

The results show that the time for replenishment ran about six months prior to the design life used. This appears to be reasonable since the satellites launched in the first year are expected to fail toward the end of their design life.

Table IX shows the time frame when the system fell below the minimum acceptable number (18) of satellites.

Table IX. Time Frame for Replenishment (Runs 16-27)

Simulation	Design Life	Time When Constellation Fell Below 18 Functional Satellites
16	90 months	84 months
17	90 months	84 months
18	90 months	85 months
19	90 months	85 months
20	120 months	115 months
21	120 months	115 months
22	120 months	116 months
23	120 months	114 months
24	180 months	175 months
25	180 months	175 months
26	180 months	176 months
27	180 months	174 months

Before continuing, it would be useful to review the satellite and point availability curves for all the simulations. These are located in the appendices, starting with Appendix B. The availability curves give a better visual representation of constellation performance over 20 years. The most important curves to examine are the baseline curves that use a satellite design life of 7.5 years and a reliability through final orbit insertion of 94%. The satellite availability curve (using replenishment) for these parameter values is shown in Figure 12. The corresponding point availability curve is shown in Figure 27. Finally, the satellite availability curve (no replenishment) for the original block buy is shown in Figure 42 for the baseline case.

Appendix B contains the point availability curves from the Aerospace Corporation using a fixed launch schedule for

maintaining 21 satellites as well as a strategy in which the launch decision is made 10 months prior to launch. Appendix C and D show the satellite and point availability curves for simulations 1-15. Finally, Appendix E provides the satellite availability curves for simulations 16-27 in which there were no replenishment launches beyond the original 28 satellites.

Satellite Attrition Analysis

An attrition analysis was performed on the Walker 18/6/2 plus three spares constellation. There were eight constellations tested with deleted satellites for coverage in 10 major areas. In each case, the output included the maximum number of satellites in the FOV continuously and the system availability reported as a percentage.

The primary objective of this analysis was two-fold. First, the analysis was to determine how many satellites could be lost before system availability fell below 95%. Secondly, it was very important to identify those areas in which navigation was adversely affected.

In run #1, there were no satellites deleted from the 21 satellite constellation. In Table X, one can see that only two areas failed to maintain 100% system availability--the Middle East and Australia. Both of these areas are at the mid latitudes and it was expected that outages would occur here.

Satellite #1 was selected for deletion in the second run. Once again, the Middle East and Australia were affected with system availabilities of 88% and 96% respectively. Also, the higher mid latitudes of Europe were degraded to a 96% availability. However, the global average was still very high--98.33.

The analysis of satellite attrition involving two satellite deletions included losses from the same orbital plane, adjacent planes and finally from alternate planes. The satellites deleted

Table X. SATELLITE ATTRITION ANALYSIS

LOCATION AREA CITY	LATITUDE LONGITUDE	SATELLITES AVAILABLE IN CONSTELLATION FOR SIMULATION 21	20	19	19	19	18	18	18
		AVAILABLE SATELLITES/SYSTEM AVAILABILITY							
Middle East Tel Aviv	32.05 34.46	4/96.0	3/88.0	3/88.0	3/88.0	3/88.0	3/80.0	3/88.0	3/84.0
Far East Tokyo	35.40 139.45	5/100.	4/100.	4/100.	4/84.0	4/100.	4/100.	4/84.0	3/88.0
Far East Manilla	14.31 121.01	6/100.	5/100.	5/96.0	5/100.	5/100.	5/96.0	5/100.	4/84.0
Europe Berlin	52.50 13.40	5/100.	4/96.0	4/96.0	4/92.0	4/96.0	4/92.0	4/84.0	4/96.0
Scandinavia Tromso	69.65 18.93	6/100.	5/100.	5/100.	4/96.0	5/100.	5/96.0	4/84.0	5/100.
N. Atlantic Thule	76.50 -61.60	6/100.	6/100.	5/100.	5/100.	5/96.0	5/96.0	4/96.0	5/96.0
N. America Omaha	41.10 -95.90	4/100.	4/100.	3/96.0	4/100.	4/96.0	3/96.0	4/88.0	4/96.0
C. America Panama	8.95 -79.60	6/100.	6/100.	5/100.	6/100.	5/100.	5/96.0	5/100.	5/100.
S. America Buenos Aires	-34.40 -58.30	5/100.	5/100.	4/100.	5/100.	4/88.0	4/92.0	4/76.0	4/88.0
S. America Brasilia	-15.70 -47.80	6/100.	6/100.	5/100.	6/100.	5/100.	5/92.0	5/100.	5/100.

Table X. SATELLITE ATTRITION ANALYSIS(CONTINUED)

LOCATION AREA CITY	LATITUDE LONGITUDE	SATELLITES AVAILABLE IN CONSTELLATION FOR SIMULATION 21	20	19	19	19	18	18	18
		AVAILABLE SATELLITES/SYSTEM AVAILABILITY							
Africa Brazzaville	-4.80 15.00	7/100.	6/100.	6/100.	6/100.	6/100.	6/100.	6/100.	5/100.
Australia Sydney	-34.00 151.00	4/96.0	4/96.0	3/92.0	4/92.0	4/96.0	3/92.0	4/92.0	3/80.0
AVERAGES									
Number of Satellites		5.33	4.83	4.33	4.67	4.50	4.33	4.33	4.17
System Availability		99.33	98.33	97.33	96.00	96.67	94.00	91.00	92.67

in runs 3-5 were: run #3, satellites 1 and 2; run #4, satellites 1 and 4; and finally run #5, satellites 1 and 7. Referring to the global averages in Table X, one can observe that the worst case involved satellite attrition in adjacent planes with a system availability of 96% versus 96.67% and 97.33% in the other two runs.

The final three runs again involved satellite losses in the same, adjacent and alternate planes. The results indicated that at this number of satellites (18), the global average falls to 91% for system availability. Once again, the loss of satellites in the adjacent planes was the worst case.

The analysis was able to rank the major regions of the world with respect to system availability given a particular attrition scenario. Table XI provides a summary of the eight runs and show the ranking among the areas. The ranking is listed below from best to worst.

Africa
Central America
North Atlantic Region
Scandinavia
North America
Europe
Far East
South America
Australia
Middle East

An area summary chart is shown in Table XII in order to see immediately which areas are adversely affected when selected satellites are chosen for degraded performance or attrition. The analysis shows that only one satellite could be degraded so that navigation accuracy is adversely affected in the Middle East while Africa, Central America and Scandinavia are virtually

Table XI. System Availability, Constellation: Walker 18 6/2 Plus 3 Spares

DELETED SATELLITES	MIDDLE EAST	FAR EAST	EUROPE	SCANDINAVIA	N.ATLANTIC	N.A.	C.A.	S.A.	AFR.	AUS.
NONE	96.	100. 100.	100.	100.	100.	100.	100.	100. 100.	100.	96.
1 SATELLITE SATELLITE #1	88.	100. 100.	96.	100.	100.	100.	100.	100. 100.	100.	96.
2 SATELLITES SATELLITES #1,2 SAME PLANE	88.	100. 96.	96.	100.	100.	96.	100.	100. 100.	100.	92.
2 SATELLITES SATELLITES #1,4 ADJACENT PLANES	88.	84. 100.	92.	96.	100.	100.	100.	100. 100.	100.	92.
2 SATELLITES SATELLITES #1,7 ALTERNATE PLANES	88.	100. 100.	96.	100.	96.	96.	100.	100. 88.	100.	96.
3 SATELLITES SATELLITES #1,2,3 SAME PLANE	80.	100. 96.	92.	96.	96.	96.	96.	92. 92.	100.	92.
3 SATELLITES SATELLITES #1,4,7 ADJACENT PLANES	88.	84. 100.	84.	84.	96.	88.	100.	100. 76.	100.	92.
3 SATELLITES SATELLITES #1,7,13 ALTERNATE PLANES	84.	88. 84.	96.	100.	96.	96.	100.	100. 88.	100.	80.
AVERAGES	87.5	93.0	94.0	97.0	98.0	96.5	99.5	93.0	100.	92.

AREA COVERAGE BEST...WORST
AFRICA/C.A./N.ATL./SCAND./N.A./EUR./FAR E.,S.A./AUS./MIDDLE EAST

CITIES USED: MIDDLE EAST, TEL AVIV; FAR EAST, TOKYO, MANILLA; EUROPE, BERLIN; SCANDINAVIA, TROMSO; N. ATLANTIC, THULE; N. AMERICA, OMAHA; C. AMERICA, PANAMA; S. AMERICA, BRASILIA, BUENOS AIRES; AFRICA, BRAZZAVILLE; AUSTRALIA, SYDNEY

Table XII. System Availability Area Summary

DELETED SATELLITES	SYSTEM AVAILABILITY 76%	80%	84%	88%	92%	96%	100%
NONE						M.EAST AUS.	F.EAST,EUR.,SCAND. N.ATL.,N.A.,C.A., S.A.,AFRICA
SATELLITE #1				M.EAST		AUS. EUR.	F.EAST,SCAND., N.ATL.,N.A.,C.A., S.A.,AFRICA
SATELLITES #1,2 SAME PLANE				M.EAST	AUS.	EUR. N.A.	F.EAST,SCAND., N.ATL.,C.A.,S.A., AFRICA
SATELLITES #1,4 ADJACENT PLANES			F.EAST	M.EAST	AUS. EUR.	SCAND.	N.ATL.,N.A.,C.A., S.A.,AFRICA
SATELLITES #1,7 ALTERNATE PLANES				M.EAST S.A.		AUS. EUR. N.ATL. N.A.	F.EAST,SCAND., C.A.,AFRICA
SATELLITES #1,2,3 SAME PLANE		M.EAST			AUS. EUR. S.A.	F.EAST SCAND. N.A.,C.A	AFRICA
SATELLITES #1,4,7 ADJACENT PLANES	S.A.		F.EAST EUR. SCAND.	N.A. M.EAST	AUS.	N.ATL.	C.A.,AFRICA
SATELLITES #1,7,13 ALTERNATE PLANES		AUS.	F.EAST M.EAST	S.A.		EUR. N.ATL. N.A.	C.A.,SCAND., AFRICA

unaffected. The overall results for the satellite attrition analysis indicate that the mid latitudes in both the northern and southern hemispheres are subject to immediate degraded system performance. The extent of the degradation depends on the positions of the satellites lost.

In this chapter, the analysis of the EGAD model determined that 21 satellites are the minimum threshold number of satellites to operate GPS with a high degree of system availability. Using this threshold, the Replenishment Launch Strategy model tested 15 simulations where replenishment of the original 28 satellites was allowed. In each case, the optimum time interval between replenishment launches was found. For the baseline case of a 7.5 year design life and 94% reliability through final orbit insertion, the optimum interval was 3.9 months between launches after the third year. The simulation maintained a .99 point availability for 21 satellites over the 20 year period. The estimated number of satellites required was 74 at a cost in FY 86 dollars of $5.48 Billion.

The last 12 simulations evaluated by the Replenishment Launch Strategy model were used to determine the duration of the original block buy of 28 satellites. No replenishment launches were allowed. The analysis showed that the system will operate above 18 satellites for about 85 months given the baseline estimates for satellite design life and reliability through final orbit insertion.

In the last section of this chapter, the EGAD model was evaluated using the Walker 18/6/2+3 constellation. Up to three

satellites were deleted in the same, adjacent or alternate planes. The results indicate that Africa and the equatorial regions are virtually unaffected by satellite attrition, while the Middle East and other mid latitude regions experience the most performance degradation. A final interesting result is that satellite attrition in adjacent planes causes the most degradation in system performance.

The final chapter of this report includes a review of the research performed and a presentation of specific conclusions and recommendations.

V. Conclusions and Recommendations

Conclusions

The primary objective of this research was to address several operational issues proposed by the Air Force Space Division. The key areas were to validate the recommended constellation configuration and to find the best plan to maintain the system over a 20 year period. Also, it is important that the program managers of GPS have a good estimate for the time frame of the next block buy of satellites.

This study concludes that the Walker 18/6/2+3 constellation recommended by the Aerospace Corporation will indeed do the job with a high degree of system availability--99.33. The research also indicates that given a satellite design life of 7.5 years for the GPS satellites and a 94% reliability through final orbit insertion, the system will need a total of 74 satellites at a cost in FY 86 dollars of $5.48 Billion or approximately $274 Million per year of operation. This plan would insure a high availability of 21 functional satellites 99% of the time.

Another interesting result is that it is possible to use a fixed launch strategy without having to make a launch decision 10 months prior. This study based its recommendations on finding the minimum fixed launch rate that would maintain the constellation at 21 satellites.

The remainder of conclusions and specific recommendations are listed on the next two pages. This information should be extremely useful to operational planners in the program office.

On the basis of the results obtained in the analysis of the EGAD and Replenishment Launch Strategy models, the following specific conclusions are drawn:

1. The current block buy of 28 satellites will meet minimum operational requirements for 85 months.

2. The replenishment phase should begin in 1989 with a launch every 3.9 months.

3. A 20 year operation of GPS requires an additional 46 satellites and these should be broken into two block buys of 23 satellites each. The first of these satellites should be available for operation in 1993.

4. An improvement in the reliability through final orbit insertion from the current 94% to 98% will save $140 Million over 20 years.

5. An improvement in satellite design life to 10 years will save $970 Million over 20 years; a savings of about ½% for every 1% increase in design life.

6. The estimated number of satellites required for operating the system over 20 years is 74 at a cost of $5.48 Billion.

7. The Middle East and other mid latitude regions are the most sensitive to satellite attrition with the worst case being attrition in adjacent planes.

Recommendations

Based on the assumptions stated initially and observations made during the investigation, the following recommendations are proposed for further study:

1. A cost benefit analysis should be made to investigate the potential savings of increasing satellite design life and reliability through final orbit insertion.

2. Further replenishment studies of GPS should be undertaken to establish the actual cost benefit of using a hard launch schedule versus one based on cancelling with a 10 month lead time.

3. Since budget dollars for GPS compete with other systems, further studies should be made incorporating the test or Block I satellites in the replenishment phase analysis.

4. Operational plans should be developed to exploit the performance characteristics of GPS with respect to selective degradation of satellites in order to deny use of the system in strategic areas.

5. Follow-on research should be made to evaluate various upper stage configurations, a multi-mission modular spacecraft, and an evaluation of both the navigation and other subsystem reliabilities.

Appendix A: Q-GERT Replenishment Launch Strategy Model

```
***************************************************
*                                                 *
*      GPS REPLENISHMENT LAUNCH STRATEGY          *
*                                                 *
*                    MODEL                        *
*                      BY                         *
*              DAVID J. ADERHOLD                  *
*                   GSO-84D                       *
*                                                 *
***************************************************
*              SIMULATIONS 1-15                   *
***************************************************
GEN,ADERHOLD,1,7,17,84,0,7,100,240,61,F,(14) 3*
SOU,10,0,1,D,M,F*
VAS,10,1,NO,1,2,IN,1*
SOU,11,0,1,D,M,F*
QUE,20/STORAGE,0,12,P,F*
VAS,20,3,UF,3*
QUE,31/GPS 1-3,0,0,D,S/1*
QUE,32/GPS 4-6,0,0,D,S/1*
QUE,33/GPS 7-9,0,0,D,S/1*
QUE,34/GPS10-12,0,0,D,S/1*
QUE,35/GPS13-15,0,0,D,S/1*
QUE,36/GPS16-18,0,0,D,S/1*
SEL,30/SELECT,SNQ,,,B,31,32,33,34,35,36*
SIN,91/FAIL #1,1,1,D,A*
SIN,92/Fail #2,1,1,D,A*
SIN,93/FAIL #3,1,1,D,A*
SIN,94/FAIL #4,1,1,D,A*
SIN,95/FAIL #5,1,1,D,A*
SIN,96/FAIL #6,1,1,D,A*
SIN,97/US FAIL,1,1,D,A*
ACT,10,10,UF,2,1/LAUNCH,1,1.0*
ACT,10,20,CO,0.0,2/STORAGE,1,1.0*
ACT,20,30,UF,4,3/BOOST,(8) 0.98*
ACT,20,97,CO,0.0,3/BOOST, (8) 0.02*
ACT,31,91,AT,1,4/OPER #1,4,1.0*
ACT,32,92,AT,1,5/OPER #2,4,1.0*
ACT,33,93,AT,1,6/OPER #3,4,1.0*
ACT,34,94,AT,1,7/OPER #4,4,1.0*
ACT,35,95,AT,1,8/OPER #5,4,1.0*
ACT,36,96,AT,1,9/OPER #6,4,1.0*
ACT,11,11,UF,5,10/STATS,1,1.0*
PAR,1,90.,0.,126.,12.*
FIN*
***************************************************
*              SIMULATIONS 16-27                  *
***************************************************
*CHANGES TO MODEL ABOVE*
*DELETE LINE 2 (SOU,10...)
*ADD LINE  QUE,10/LAUNCHES,27*
*DELETE LINE 21 (ACT,10,10...)
*CHANGE LINE 22 to ACT,10,20,UF,2,2/STORAGE,1,1.0*
```

```
 *                  Q-GERT FORTRAN INSERT PROGRAM                 *
      SUBROUTINE UI
      COMMON /QVAR/ NDE,NFTBU(100),NREL(100),NRELP(100),
     1NREL2(100),NRUN,NRUNS,NTC(100),PARAM(100,4),TBEG,TNOW
      COMMON /UCOM1/ SYSTEM,TOTAL,TM,VAL,TOT(240,61),COST(240,61),
     1SYS(240),CST(240),TH,TI,TJ,TK,TL,TN,TO
      INTEGER SYSTEM
      REAL,TM,VAL,TOTAL,TOT,COST,SYS,CST,TH,TI,TJ,TK,TL,TN,TO
      DATA TOT/14640*0./,COST/14640*0./,SYS/240*0./,CST/240*0./
      DATA TH/0./,TI/0./,TJ/0./,TK/0./,TL/0./,TN/0./,TO/0./
      SYSTEM=0
      IF (NRUN .LE. 1) TOTAL = 0
      TM=0.
      VAL=0.
      RETURN
      END
      FUNCTION UF(IFN)
      COMMON /QVAR/ NDE,NFTBU(100),NREL(100),NRELP(100),
     1NREL2(100),NRUN,NRUNS,NTC(100),PARAM(100,4),TBEG,TNOW
      COMMON /UCOM1/ SYSTEM,TOTAL,TM,VAL,TOT(240,61),COST(240,61),
     1SYS(240),CST(240),TH,TI,TJ,TK,TL,TN,TO
      GO TO (1,2,3,4,5),IFN
    * UF 1 NOT USED IN SIMULATION
    1 CONTINUE
      UF=0.
      RETURN
    * UF 2 SETS TIME INTERVAL BETWEEN LAUNCHES
    2 CONTINUE
      SYSTEM=NREL(31)+NREL(32)+NREL(33)+NREL(34)+NREL(35)+NREL(36)+
     1ISTUS(31,4)+ISTUS(32,5)+ISTUS(33,6)+ISTUS(34,7)+ISTUS(35,8)+
     2ISTUS(36,9)+NREL(20)+ISTUS(20,3)
      IF(TNOW .LE. 36.0)UF=1.7
      IF(TNOW .GT. 36.0)UF=4.0
      RETURN
    * UF 3 NOT USED IN SIMULATION
    3 CONTINUE
      UF=0.
      RETURN
    * UF 4 ADJUSTS FAILURE TIME FOR TIME SPENT IN LOW-EARTH-ORBIT
    4 CONTINUE
      UF=1.0
      TM=GATRB(1)-(TNOW-TMARK(IDUM))
      CALL PATRB(TM,1)
      RETURN
    * UF 5 COLLECTS MONTHLY STATISTICS
    5 CONTINUE
      UF=1.0
      VAL=NREL(31)+NREL(32)+NREL(33)+NREL(34)+NREL(35)+NREL(36)+
     1ISTUS(31,4)+ISTUS(32,5)+ISTUS(33,6)+ISTUS(34,7)+ISTUS(35,8)+
     2ISTUS(36,9)
      TOT(INT(TNOW),NRUN)=VAL
      COST(INT(TNOW),NRUN)=NTC(10)*0.127
```

```
      IF(NRUN .EQ. NRUNS) GO TO 9
      IF(NRUN .GT. 1) RETURN
      IF(NRUN .NE. NRUNS) RETURN
    9 IF(TNOW .LT. 240.0) RETURN
      DO 11 I=1,240
         DO 10 J=1,NRUNS
            SYS(I)=SYS(I)+TOT(I,J)
            CST(I)=CST(I)+COST(I,J)
   10 CONTINUE
      SYS(I)=SYS(I)/NRUNS
      CST(I)=CST(I)/NRUNS
      IF(SYS(I) .GE. 18)TH=TH+1
      IF(SYS(I) .GE. 19)TI=TI+1
      IF(SYS(I) .GE. 20)TJ=TJ+1
      IF(SYS(I) .GE. 21)TK=TK+1
      IF(SYS(I) .GE. 22)TL=TL+1
      IF(SYS(I) .GE. 23)TN=TN+1
      IF(SYS(I) .GE. 24)TO=TO+1
      WRITE(17,100)REAL(I),SYS(I)
   11 CONTINUE
      TH=TH/200
      IF(TH .GE. 1.0)TH=1.0
      TI=TI/204
      IF(TI .GE. 1.0)TI=1.0
      TJ=TJ/204
      TK=TK/204
      TL=TL/204
      TN=TN/204
      TO=TO/204
  100 FORMAT( 1X,F6.2,5X,F6.2)
      RETURN
      END
      SUBROUTINE UO
      COMMON /QVAR/ NDE,NFTBU(100),NREL(100),NRELP(100),
     1NREL2(100),NRUN,NRUNS,NTC(100),PARAM(100,4),TBEG,TNOW
      COMMON /UCOM1/ SYSTEM,TOTAL,TM,VAL,TOT(240,61),COST(240,61),
     1SYS(240),CST(240),TH,TI,TJ,TK,TL,TN,TO
      TOTAL=TOTAL+NTC(10)
      IF(NRUN .LT. NRUNS) RETURN
      WRITE(16,100)TOTAL/NRUNS
      WRITE(16,101)(TOTAL*0.127)/NRUNS
      WRITE(16,102)NRUNS
      WRITE(16,103)TH
      WRITE(16,104)TI
      WRITE(16,105)TJ
      WRITE(16,106)TK
      WRITE(16,107)TL
      WRITE(16,108)TN
      WRITE(16,109)TO
  100 FORMAT( 45H ESTIMATED NUMBER OF GPS SATELLITES REQUIRED: ,F6.2)
  101 FORMAT( 38H ESTIMATED OPERATING COST IN BILLIONS: ,F6.2)
  102 FORMAT( 14H REQUIRED RUNS:,I3)
```

```
103 FORMAT( 1H,"PERCENT OF TIME WITH 18 FUNCTIONAL SATELLITES:",F6.2)
104 FORMAT( 1H,"PERCENT OF TIME WITH 19 FUNCTIONAL SATELLITES:",F6.2)
105 FORMAT( 1H,"PERCENT OF TIME WITH 20 FUNCTIONAL SATELLITES:",F6.2)
106 FORMAT( 1H,"PERCENT OF TIME WITH 21 FUNCTIONAL SATELLITES:",F6.2)
107 FORMAT( 1H,"PERCENT OF TIME WITH 22 FUNCTIONAL SATELLITES:",F6.2)
108 FORMAT( 1H,"PERCENT OF TIME WITH 23 FUNCTIONAL SATELLITES:",F6.2)
109 FORMAT( 1H,"PERCENT OF TIME WITH 24 FUNCTIONAL SATELLITES:",F6.2)
    RETURN
    END
```

Appendix B: Point Availability Curves, The Aerospace Corporation

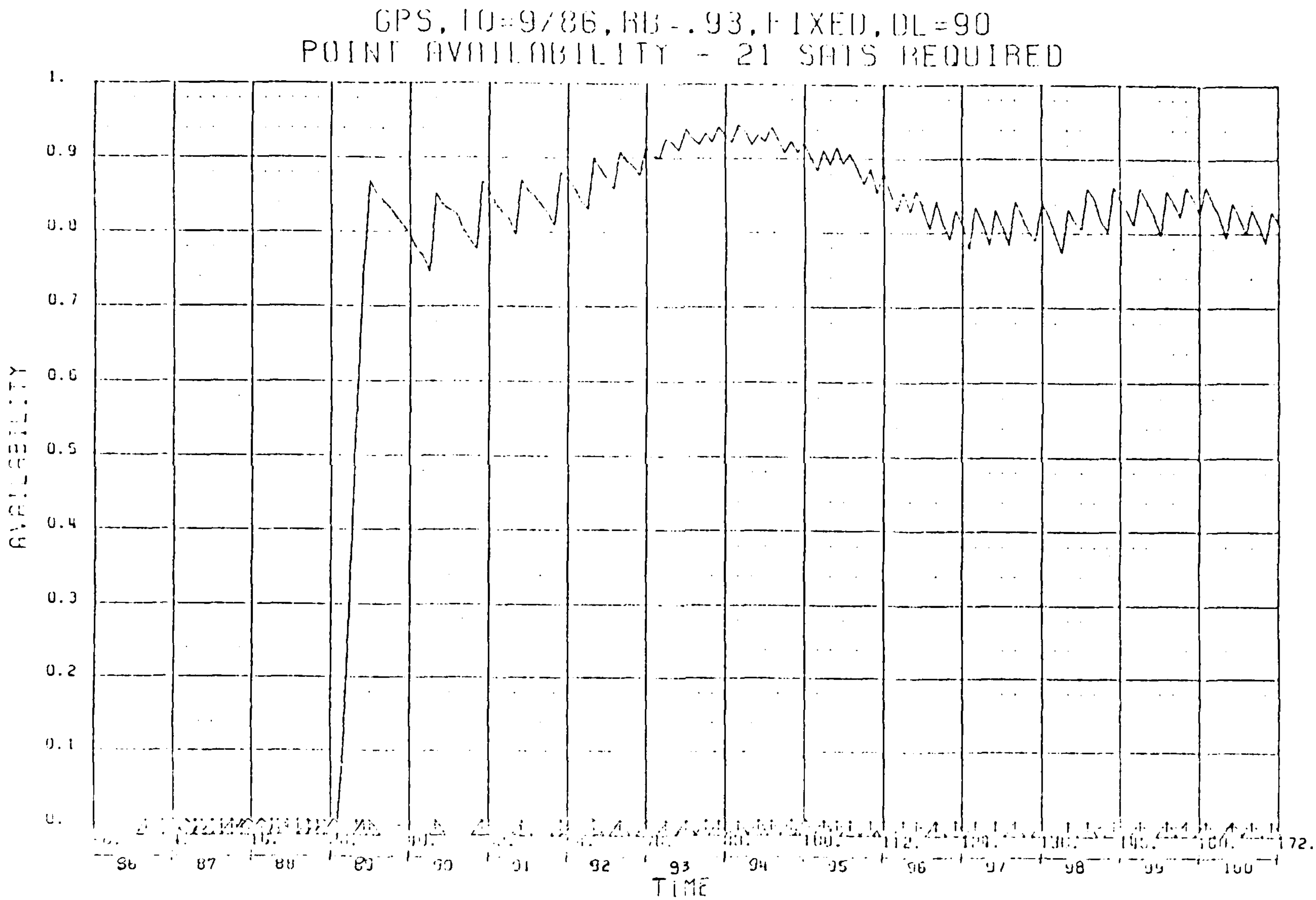


Fig. 8. Point Availability Curve for Fixed Launch Schedule, The Aerospace Corporation

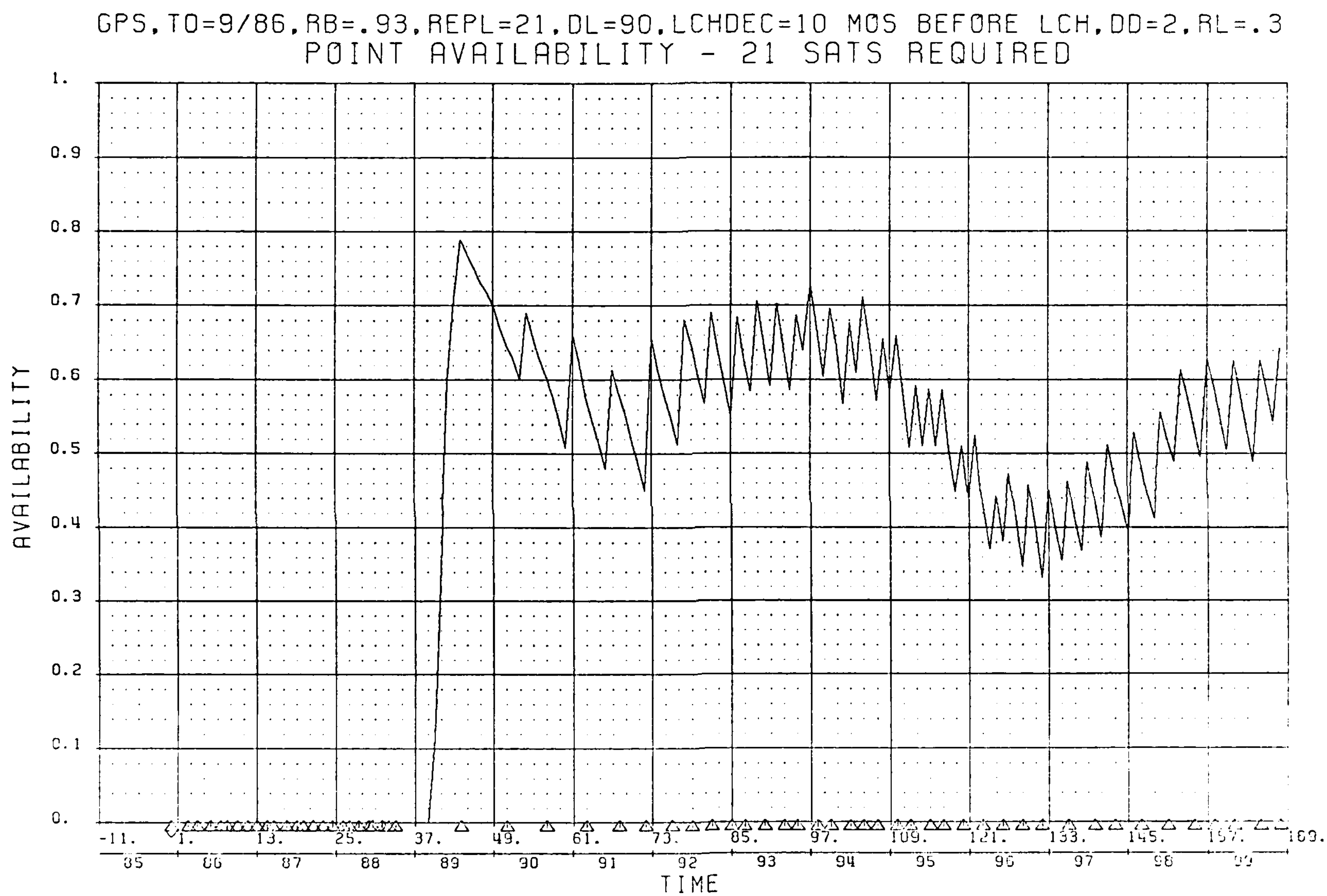


Fig. 9. Point Availability Curve for Launch Decision 10 Months Prior, Aerospace Corp.

Appendix C: Satellite Availability Curves

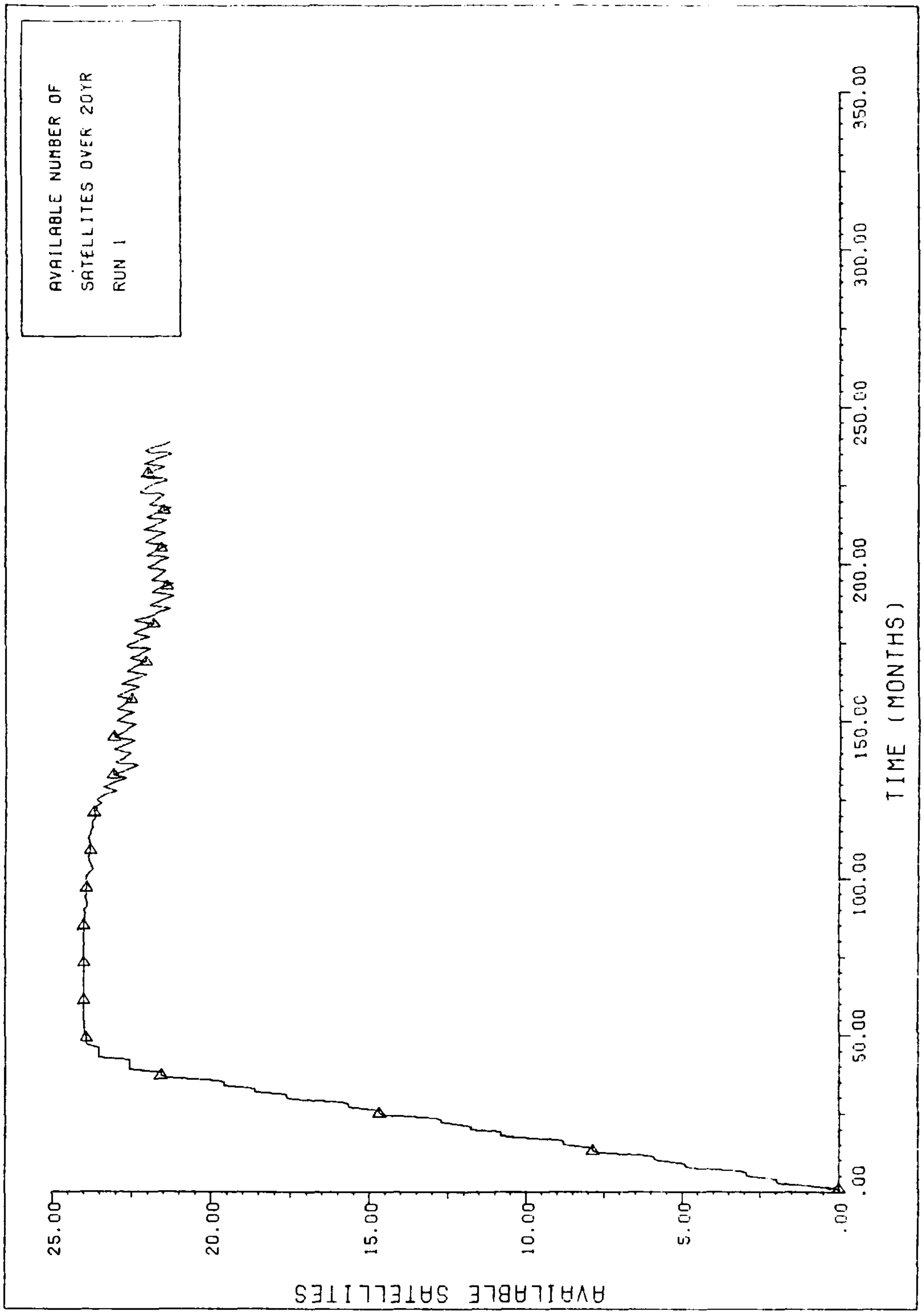


Fig. 10, SATELLITE AVAILABILITY OVER 20 YEARS, RUN 1

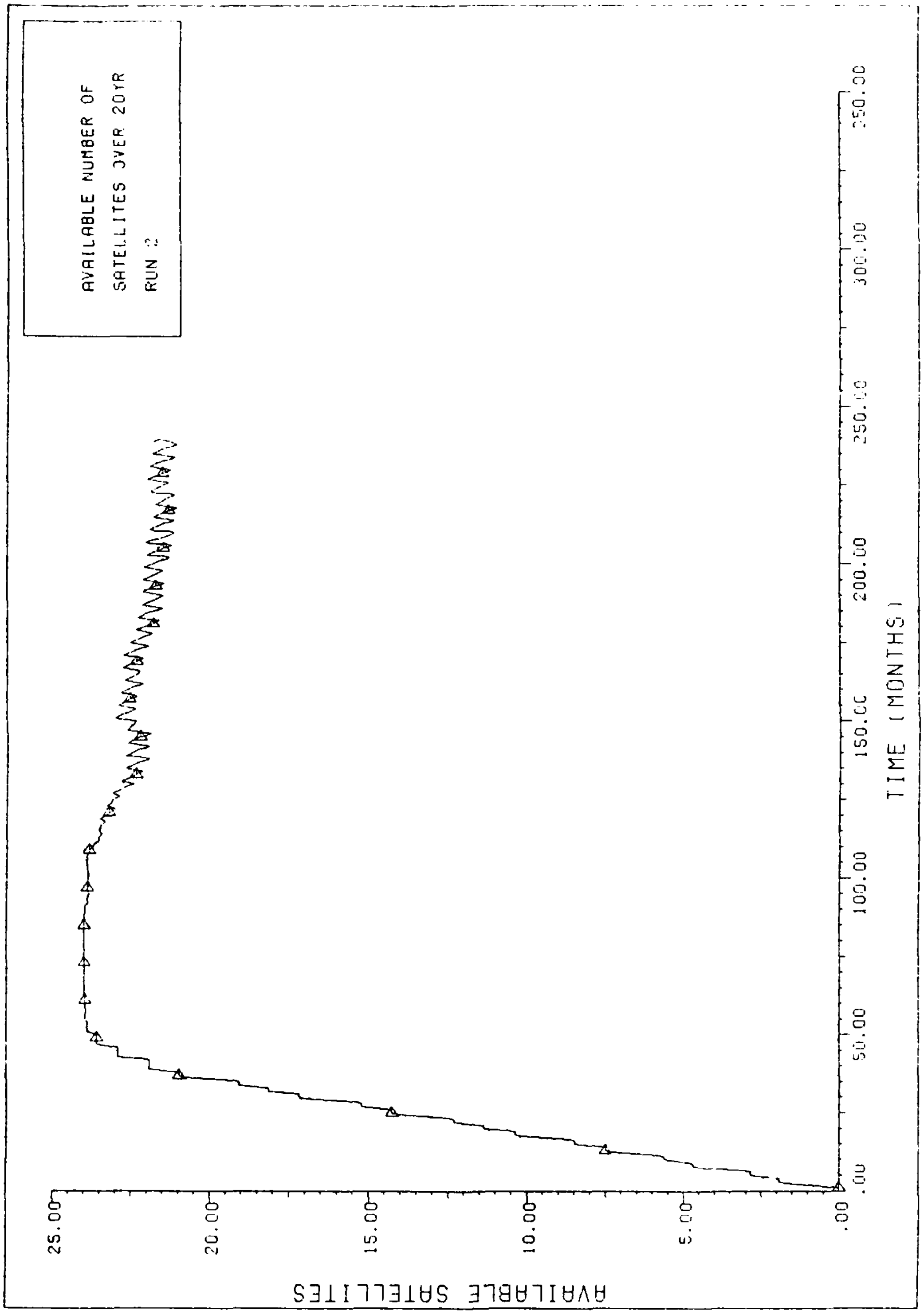


Fig. 11,SATELLITE AVAILABILITY OVER 20 YEARS, RUN 2

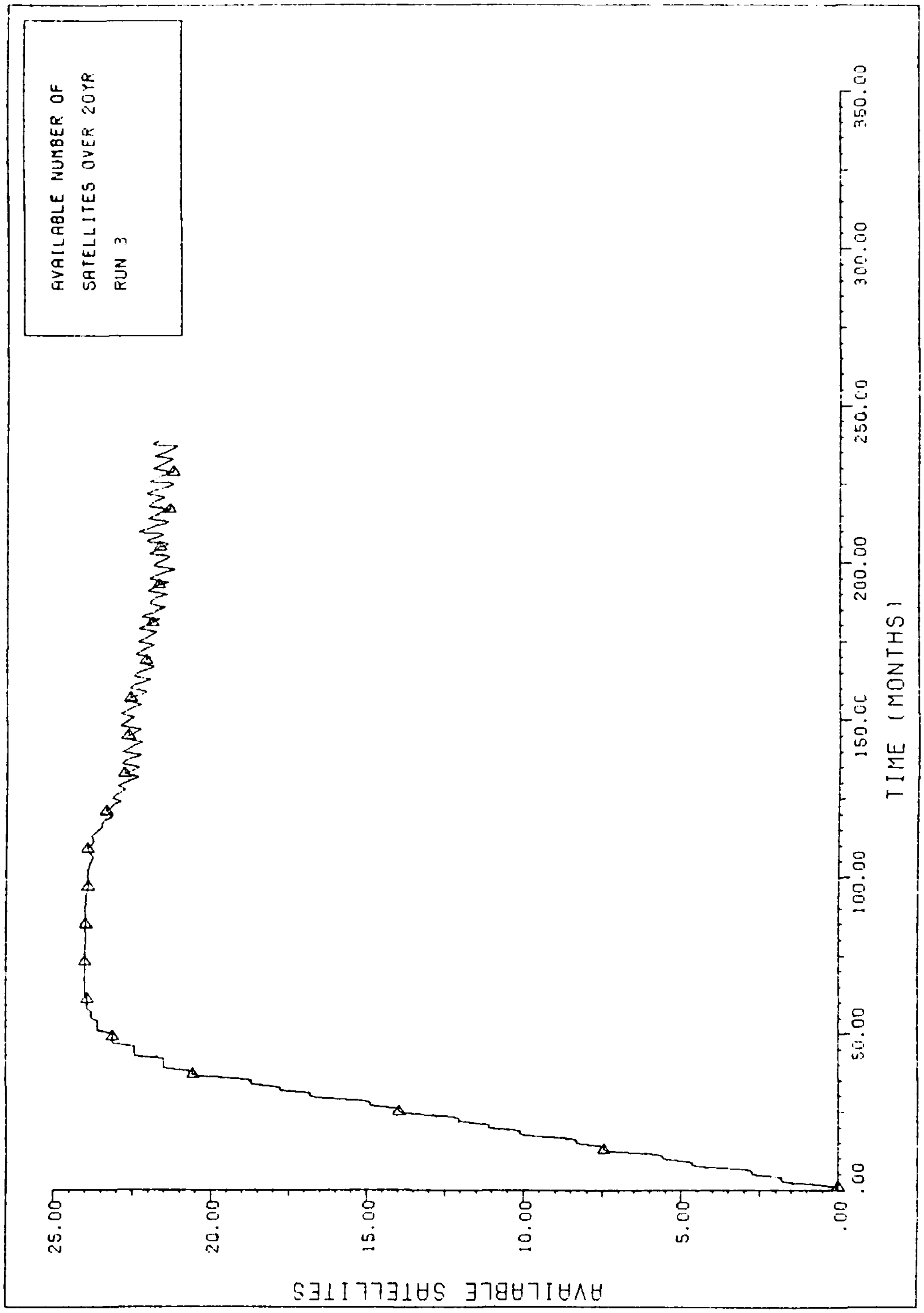


Fig. 12, SATELLITE AVAILABILITY OVER 20 YEARS, RUN 3

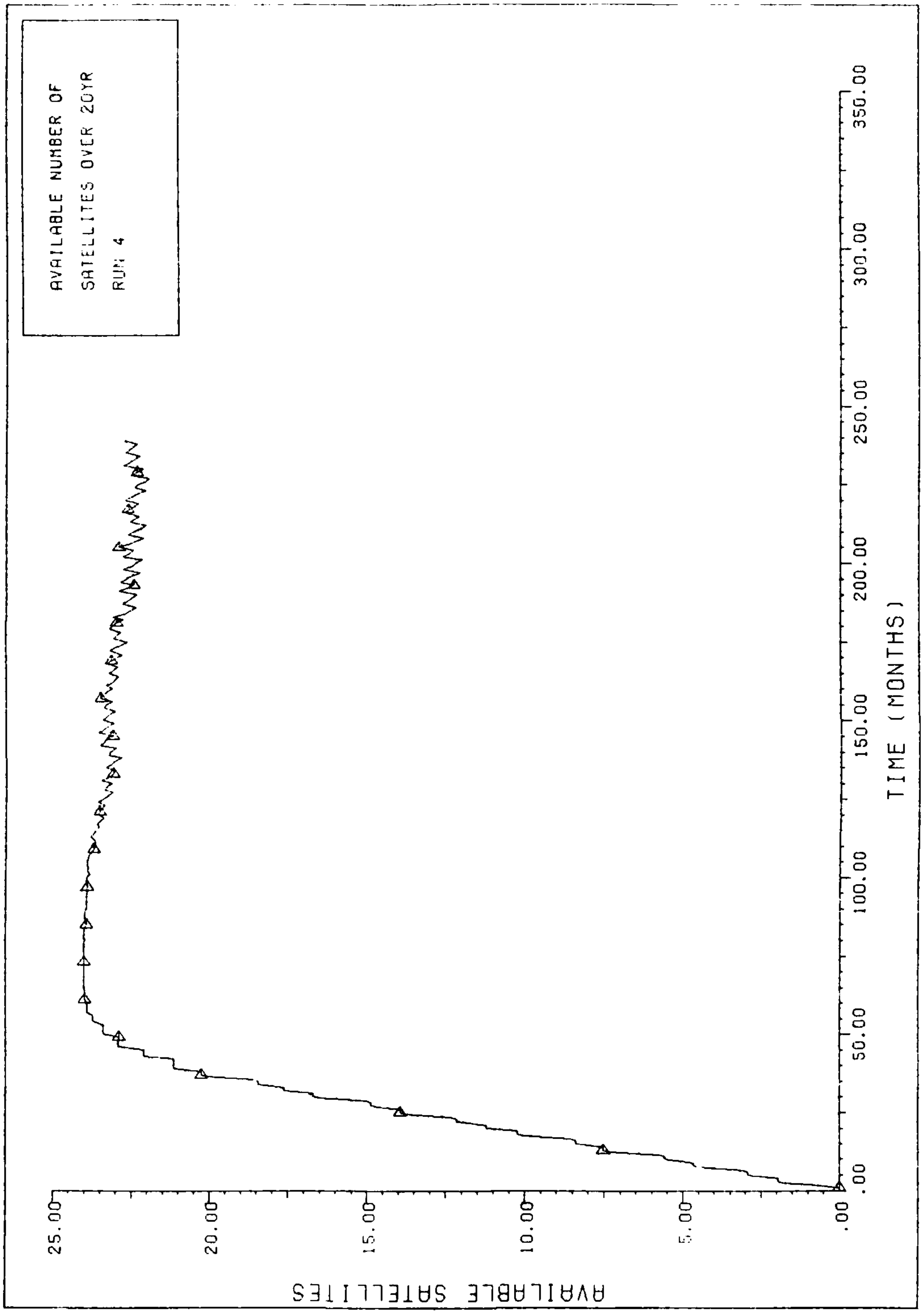


Fig. 13. SATELLITE AVAILABILITY OVER 20 YEARS. RUN 4

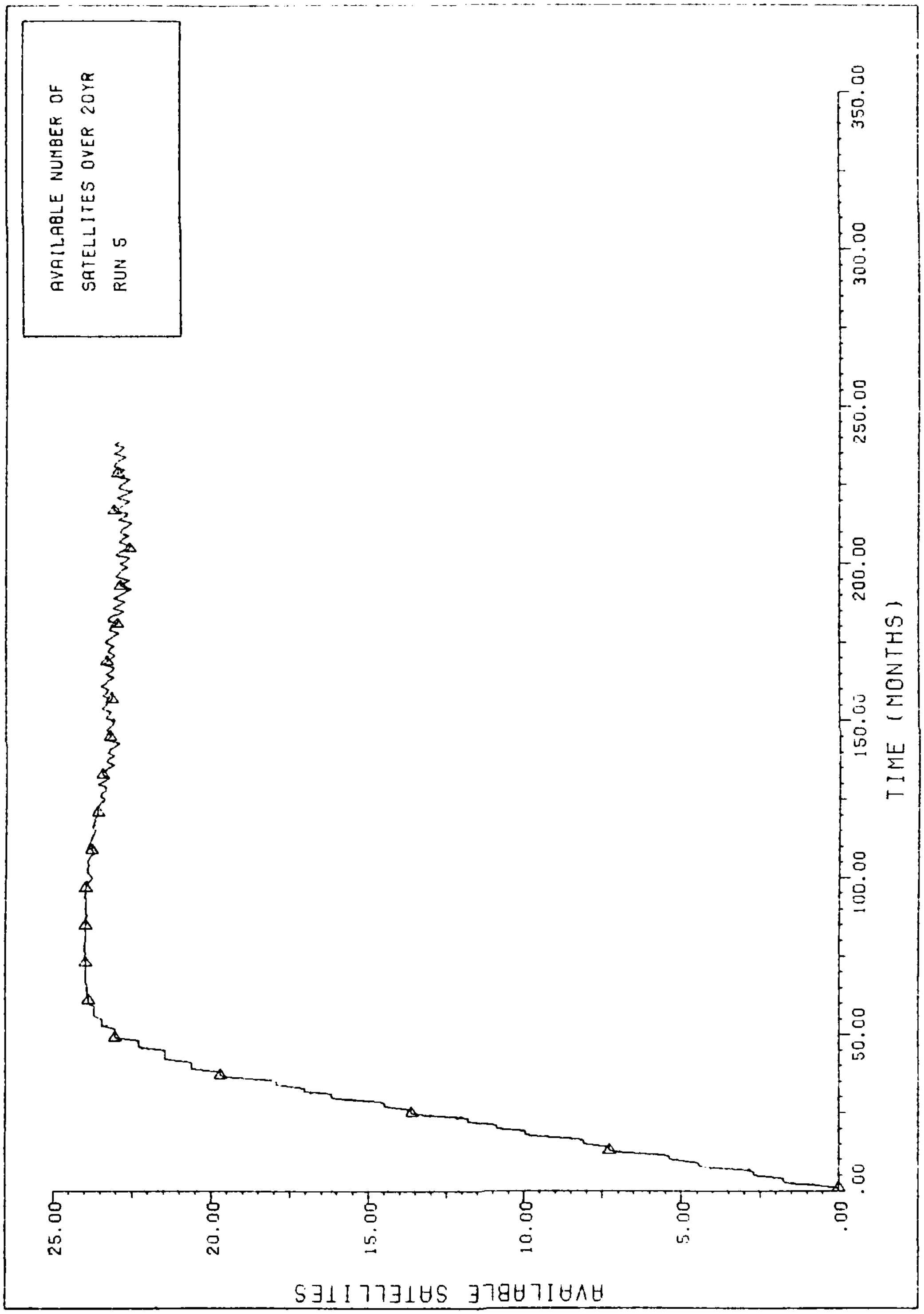


Fig. 14.SATELLITE AVAILABILITY OVER 20 YEARS. RUN 5

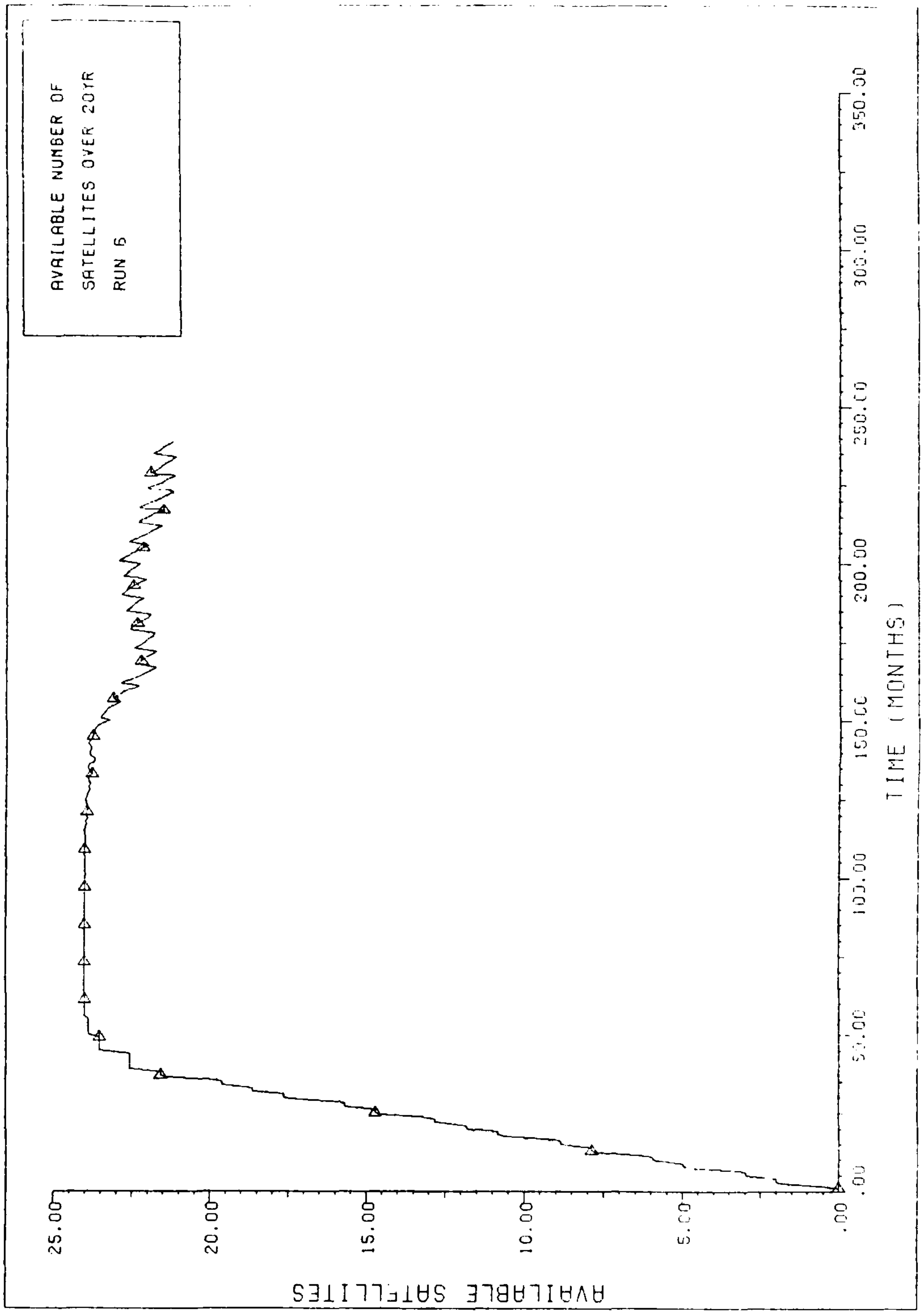


Fig. 15 SATELLITE AVAILABILITY OVER 20 YEARS, RUN 5

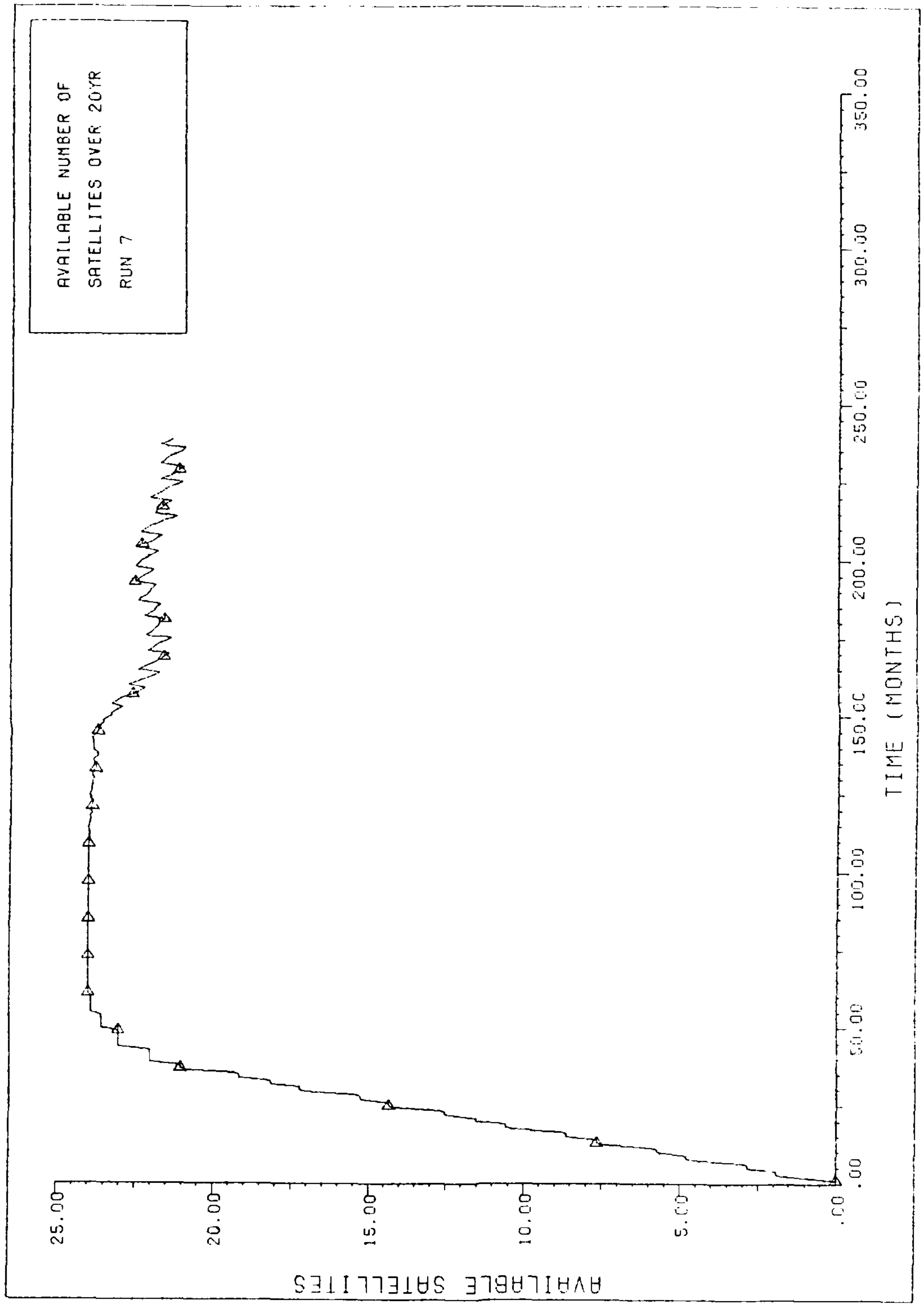


Fig. 16. SATELLITE AVAILABILITY OVER 20 YEARS. RUN 7

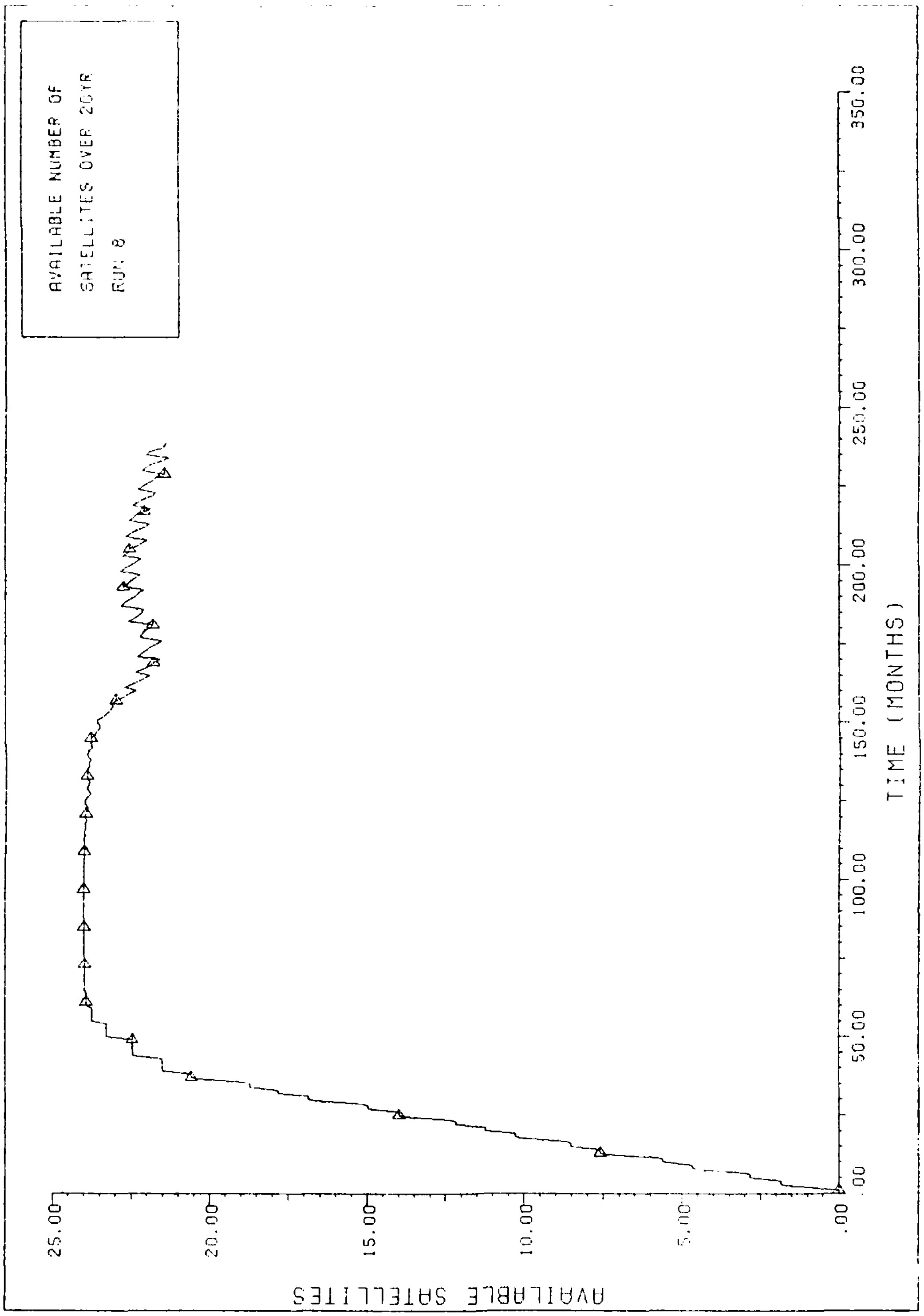


Fig. 17 SATELLITE AVAILABILITY OVER 20 YEARS. RUN 8

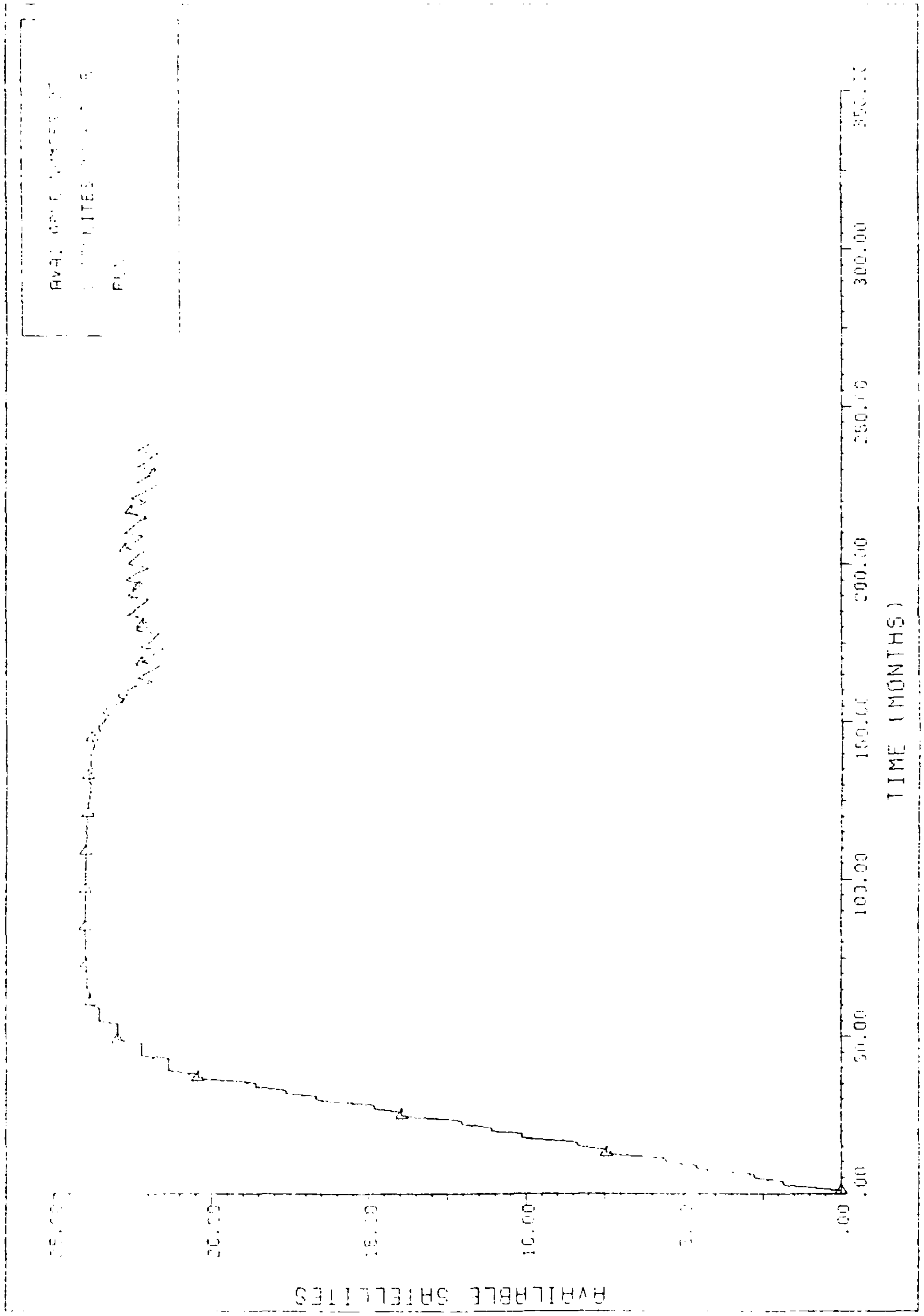


Fig. 18. SATELLITE AVAILABILITY OVER 20 YEARS, [illegible]

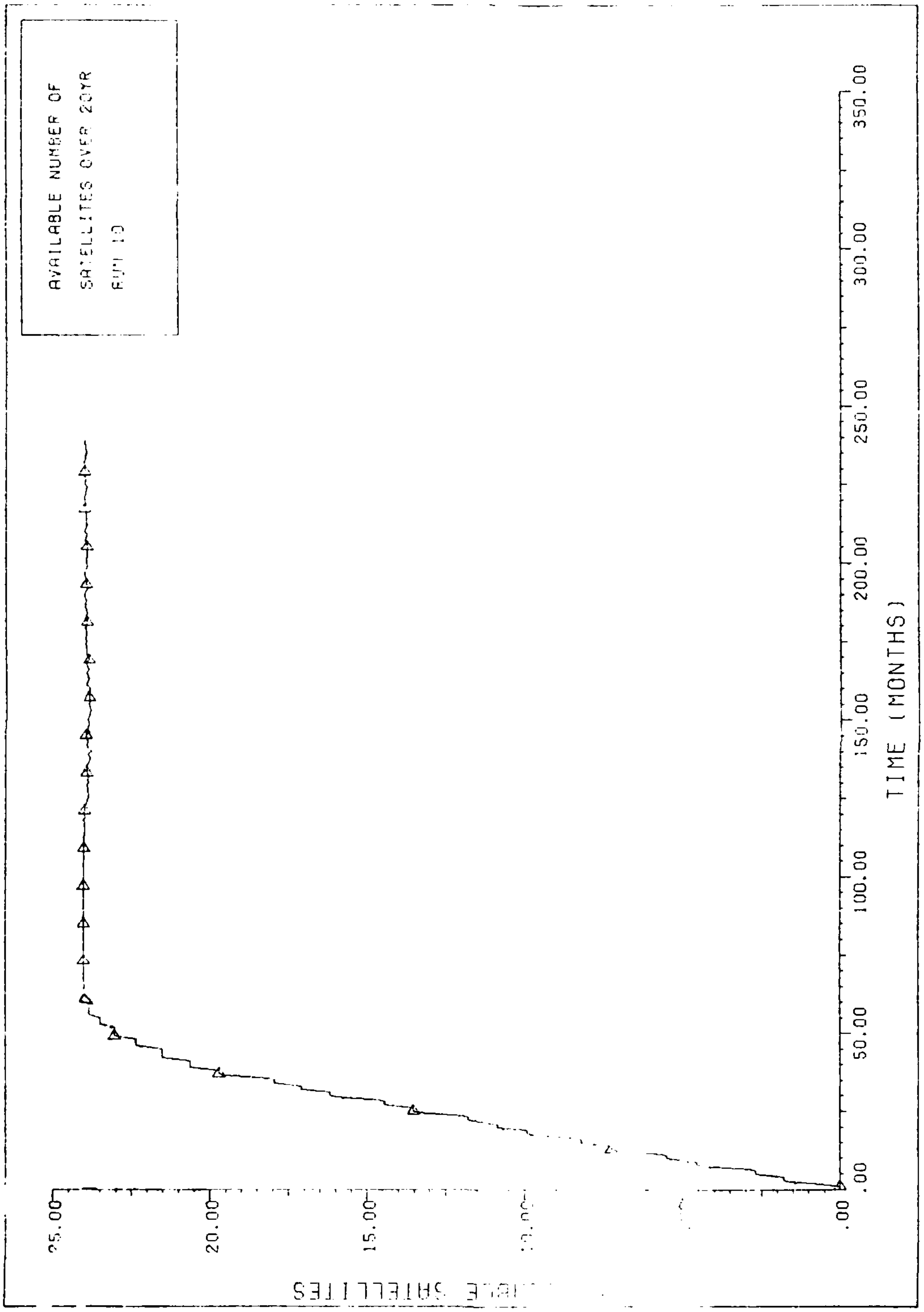


Fig. 19. SATELLITE AVAILABILITY OVER 20 YEARS. RUN 10

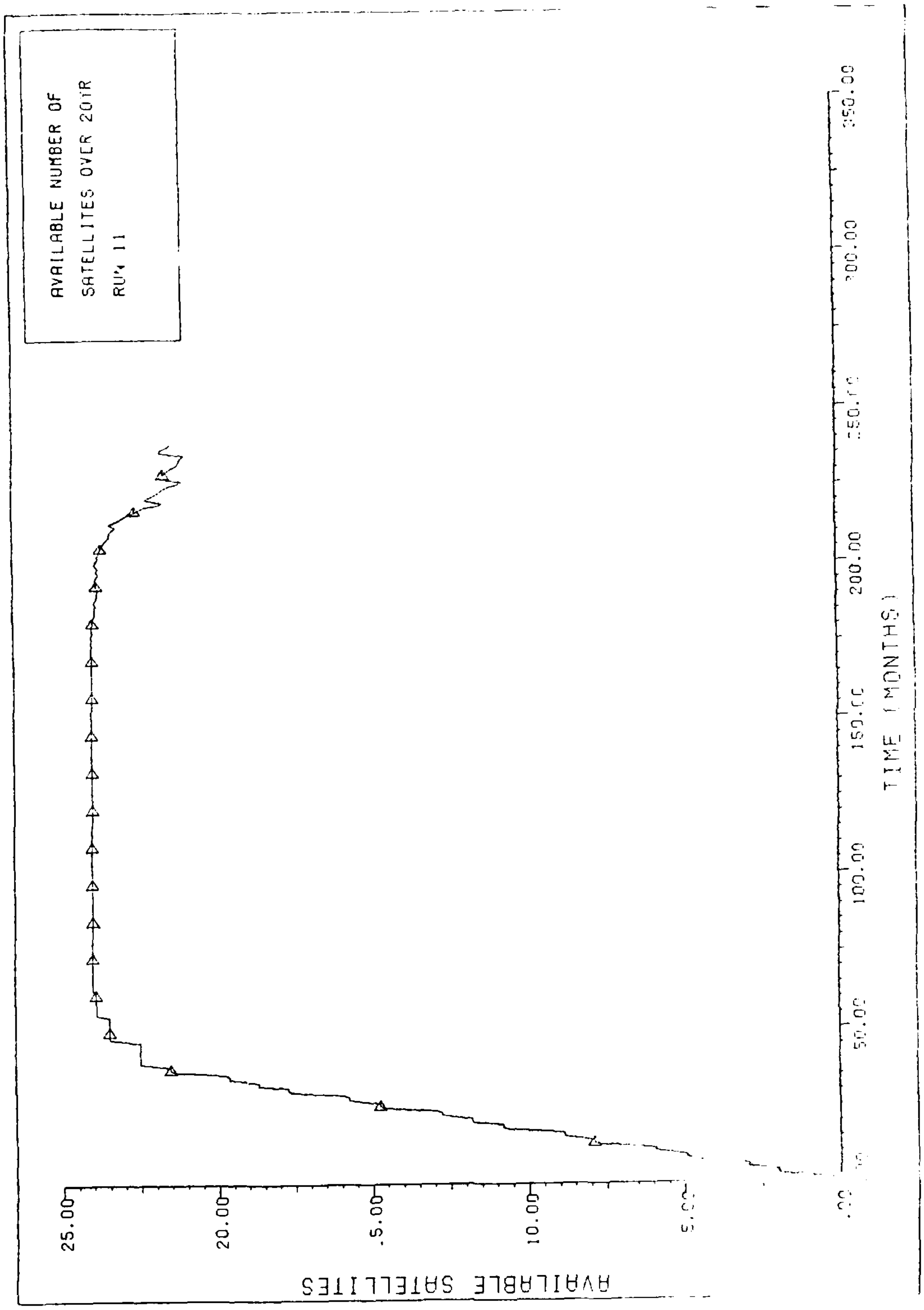


Fig. 20, SATELLITE AVAILABILITY OVER 20 YEARS, RUN 11

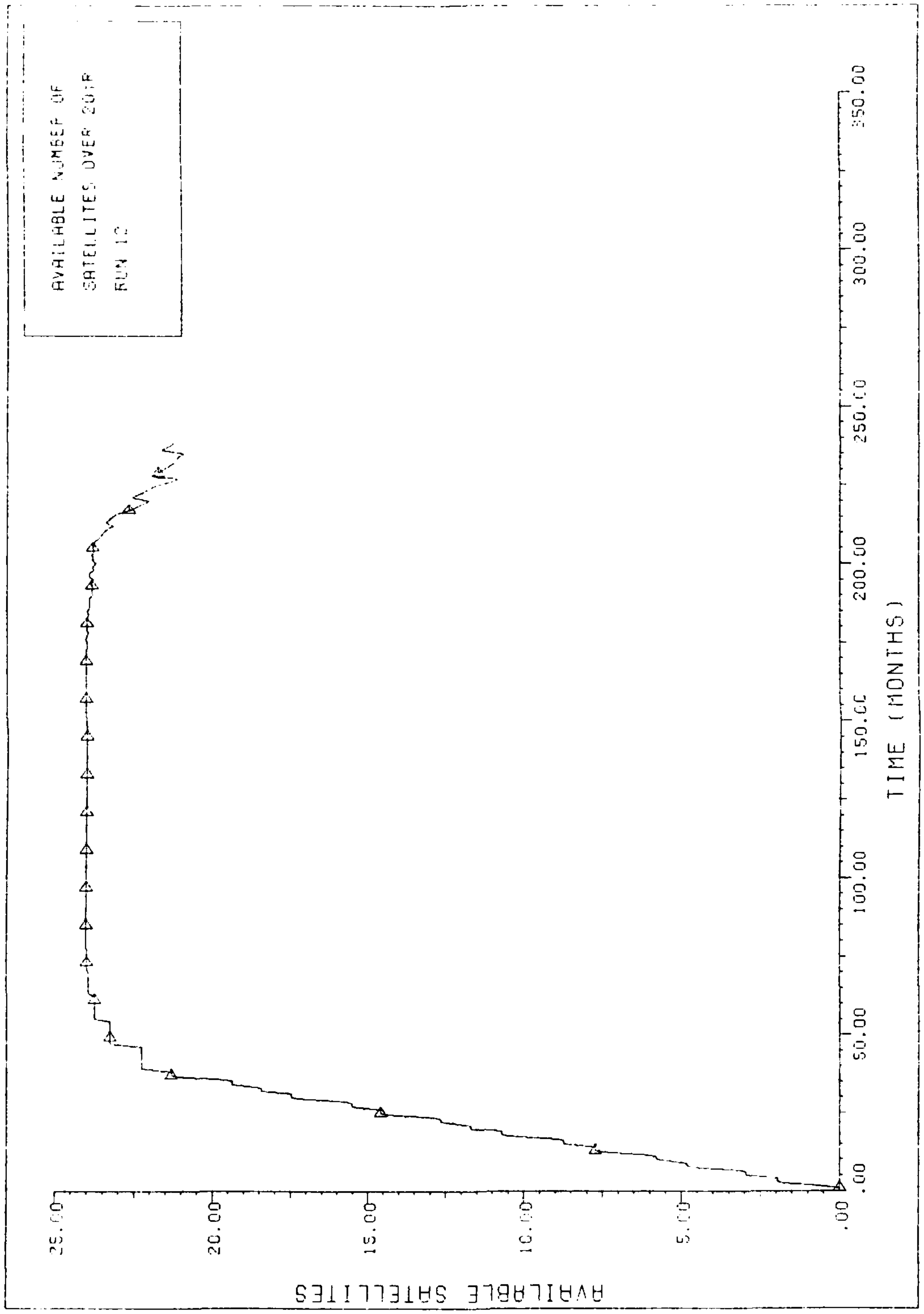


Fig. 21. SATELLITE AVAILABILITY OVER 20 YEARS, RUN 12

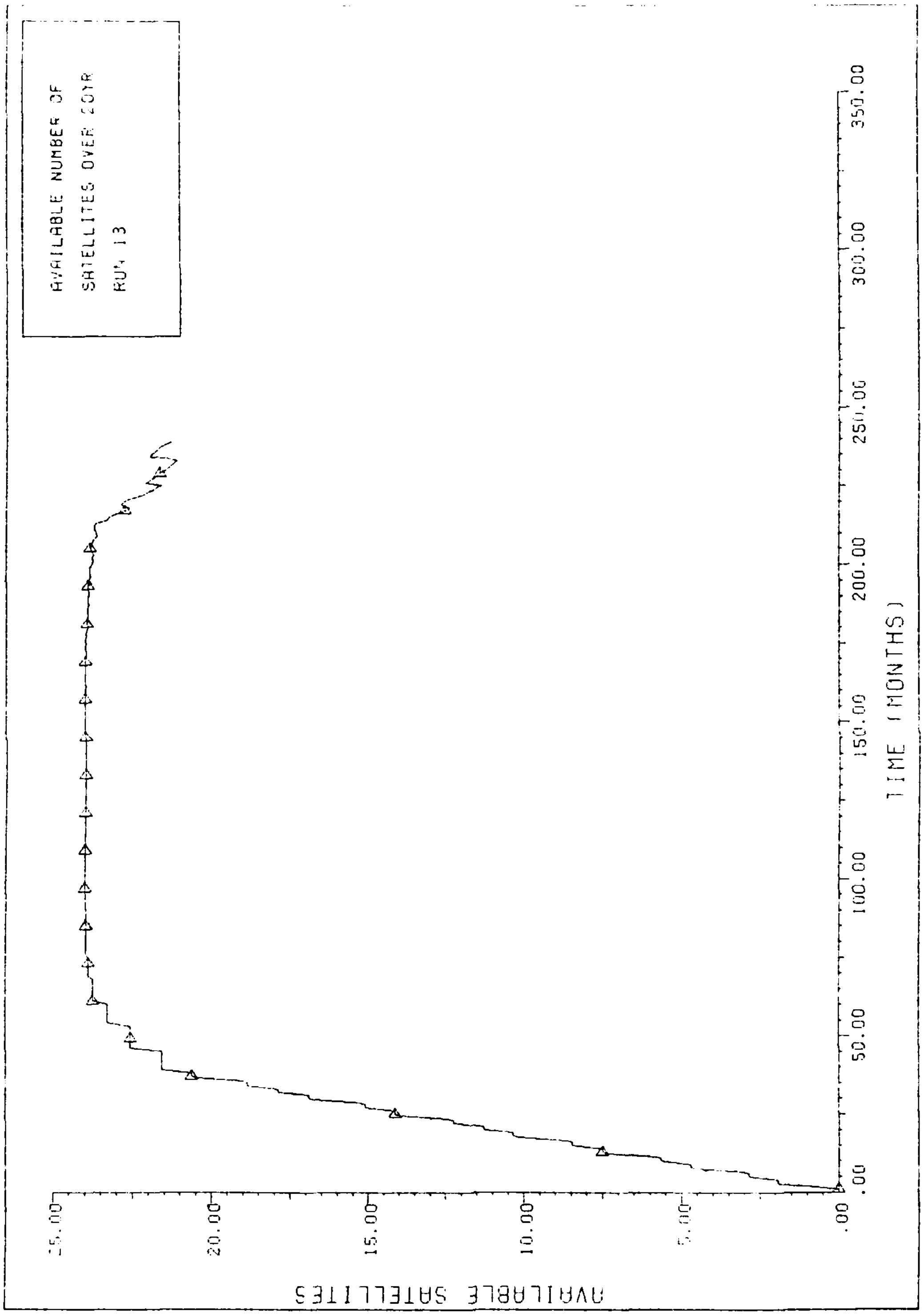


Fig. 22.SATELLITE AVAILABILITY OVER 20 YEARS, RUN 13

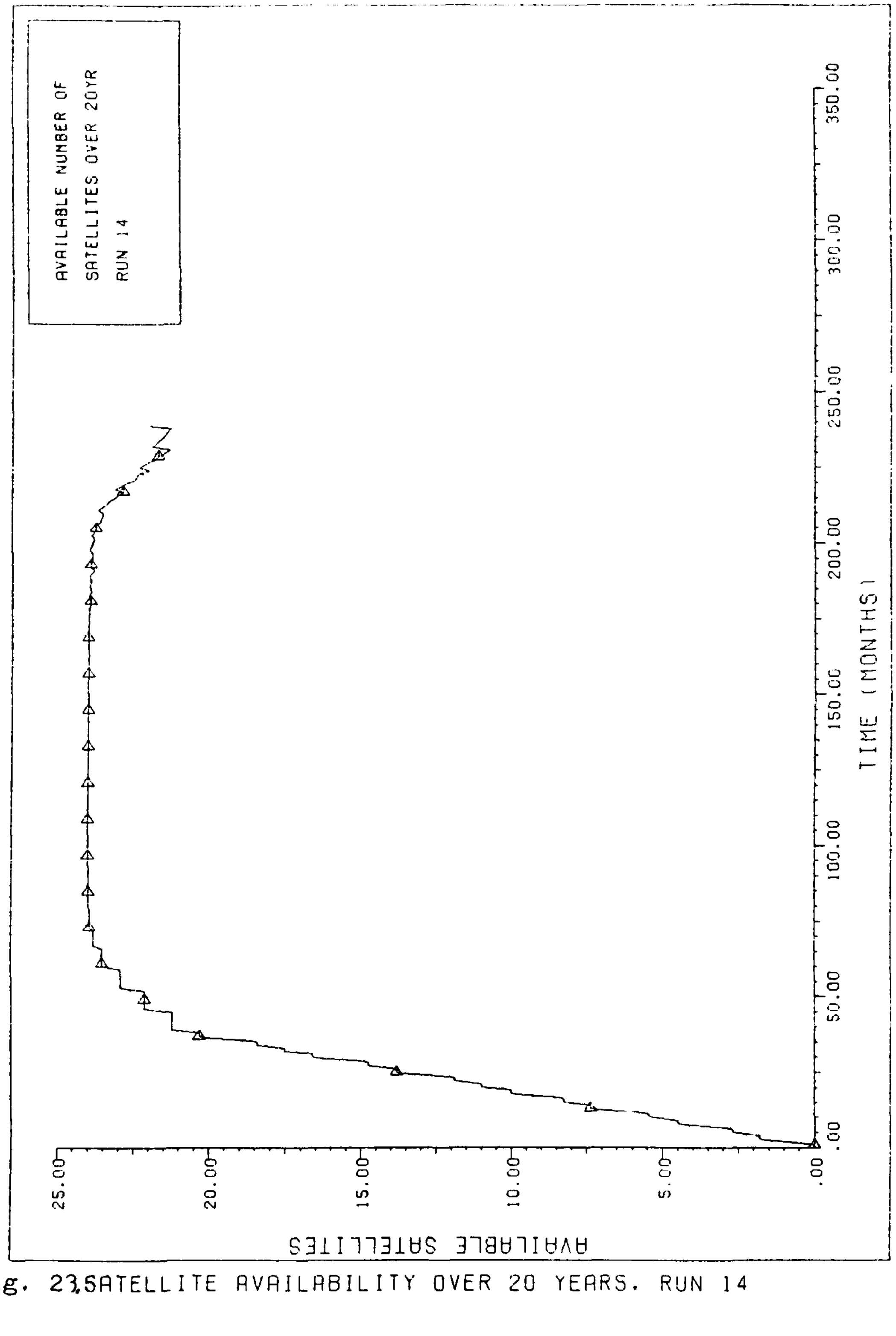


Fig. 23 SATELLITE AVAILABILITY OVER 20 YEARS. RUN 14

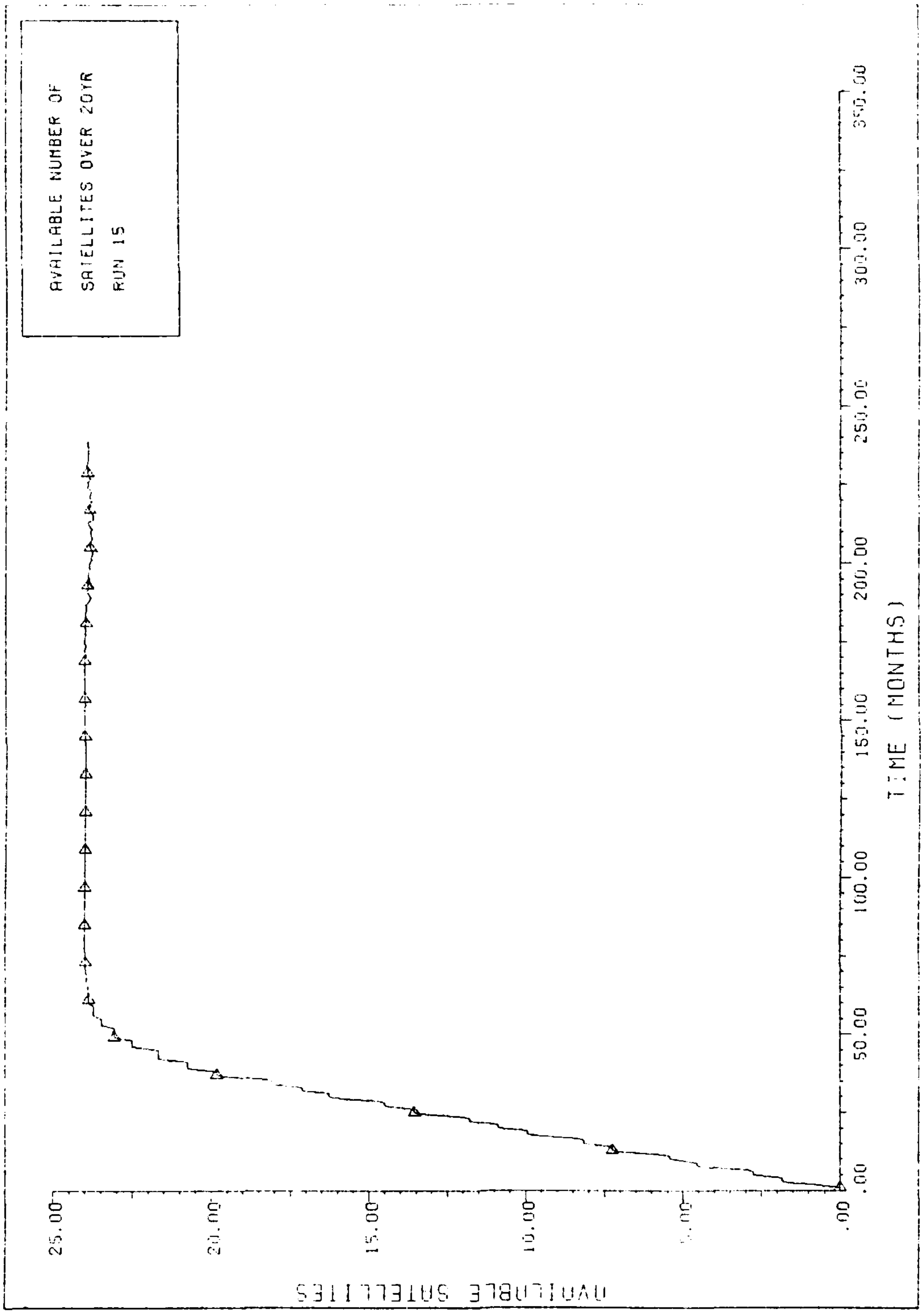


Fig. 24 SATELLITE AVAILABILITY OVER 20 YEARS. RUN 15

Appendix D: Percent Availability Curves

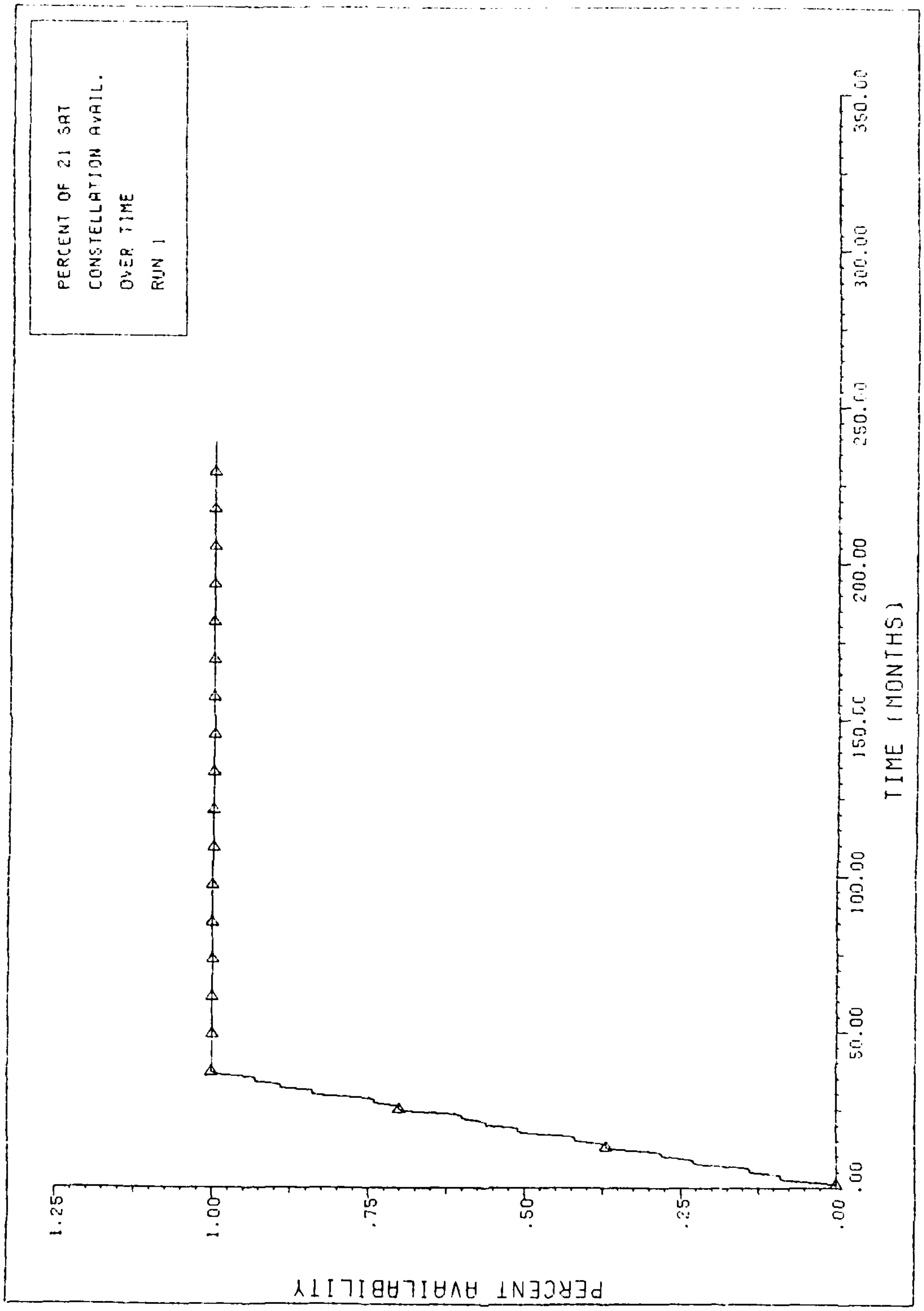


Fig. 25. 21 SATELLITE CONSTELLATION PERCENTAGE AVAILABILITY

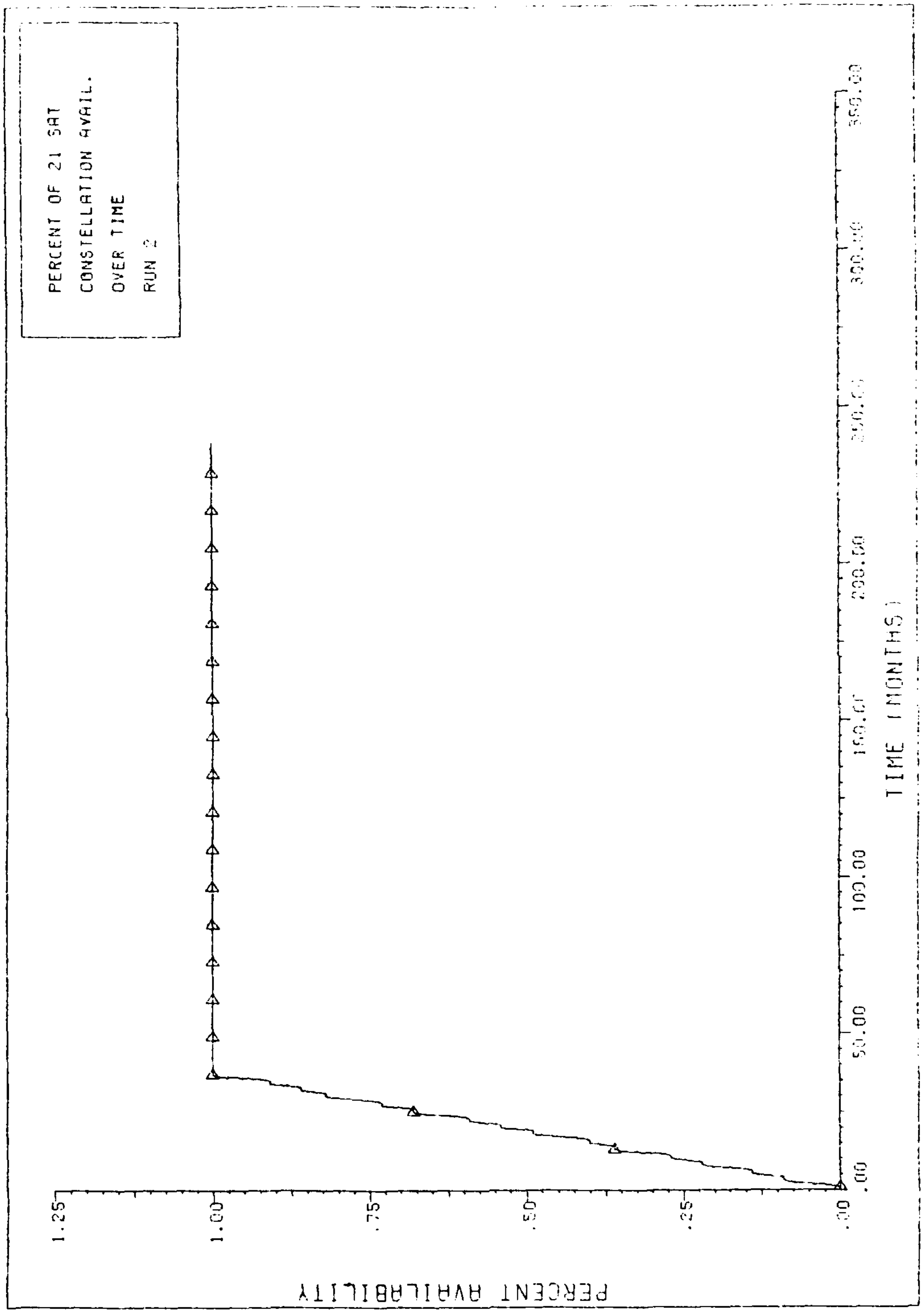
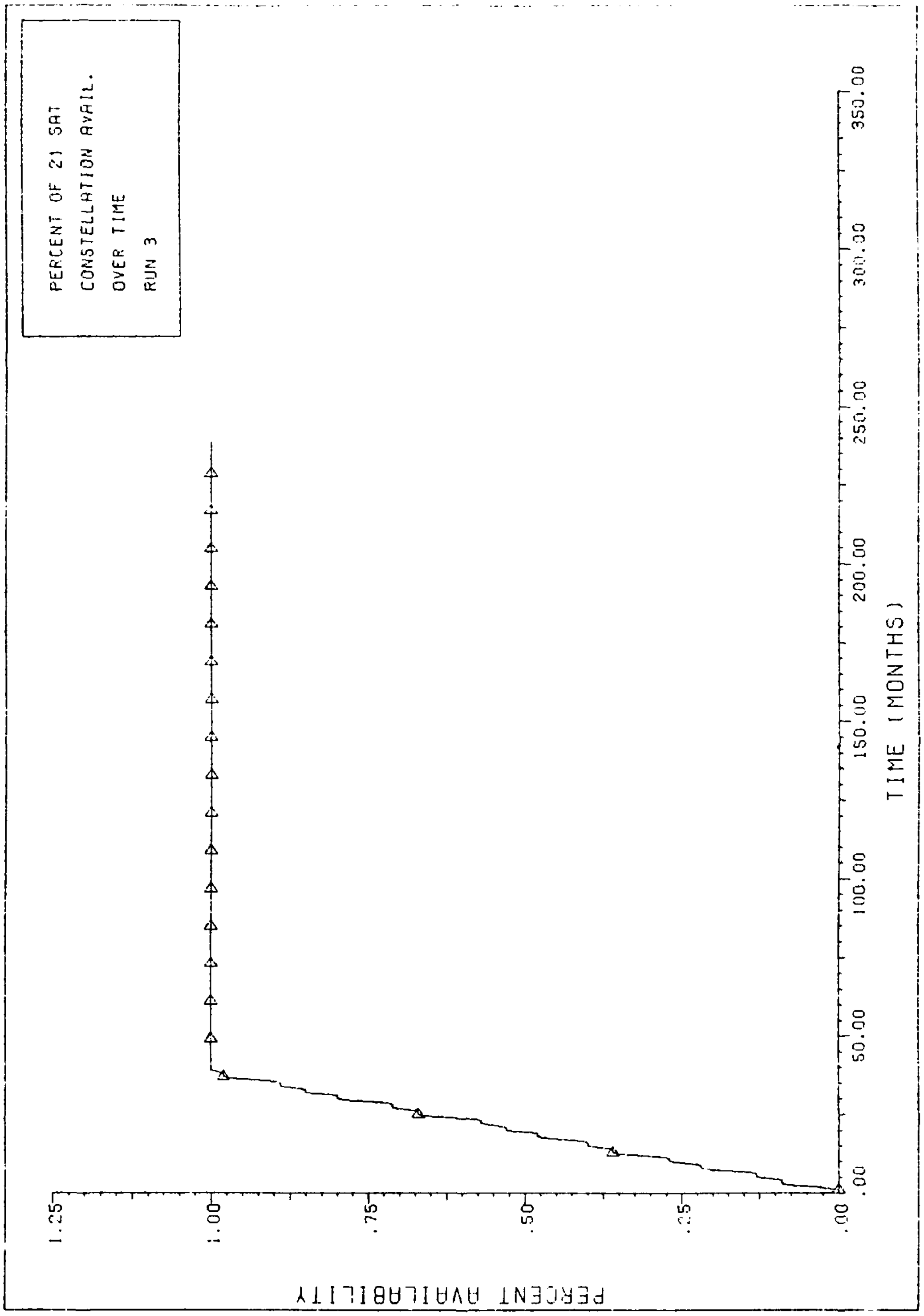


Fig. 26.21 SATELLITE CONSTELLATION PERCENTAGE AVAILABILITY



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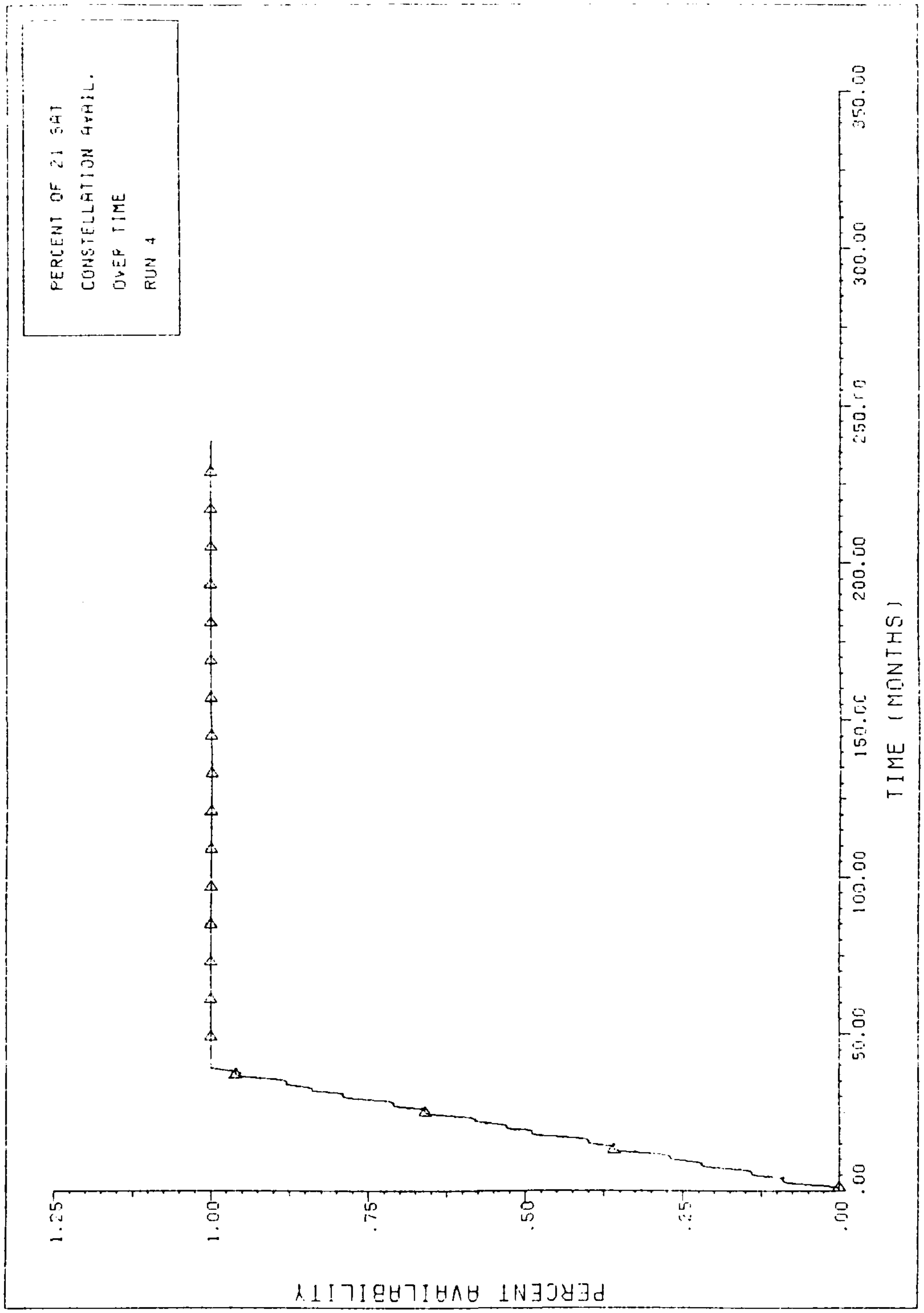
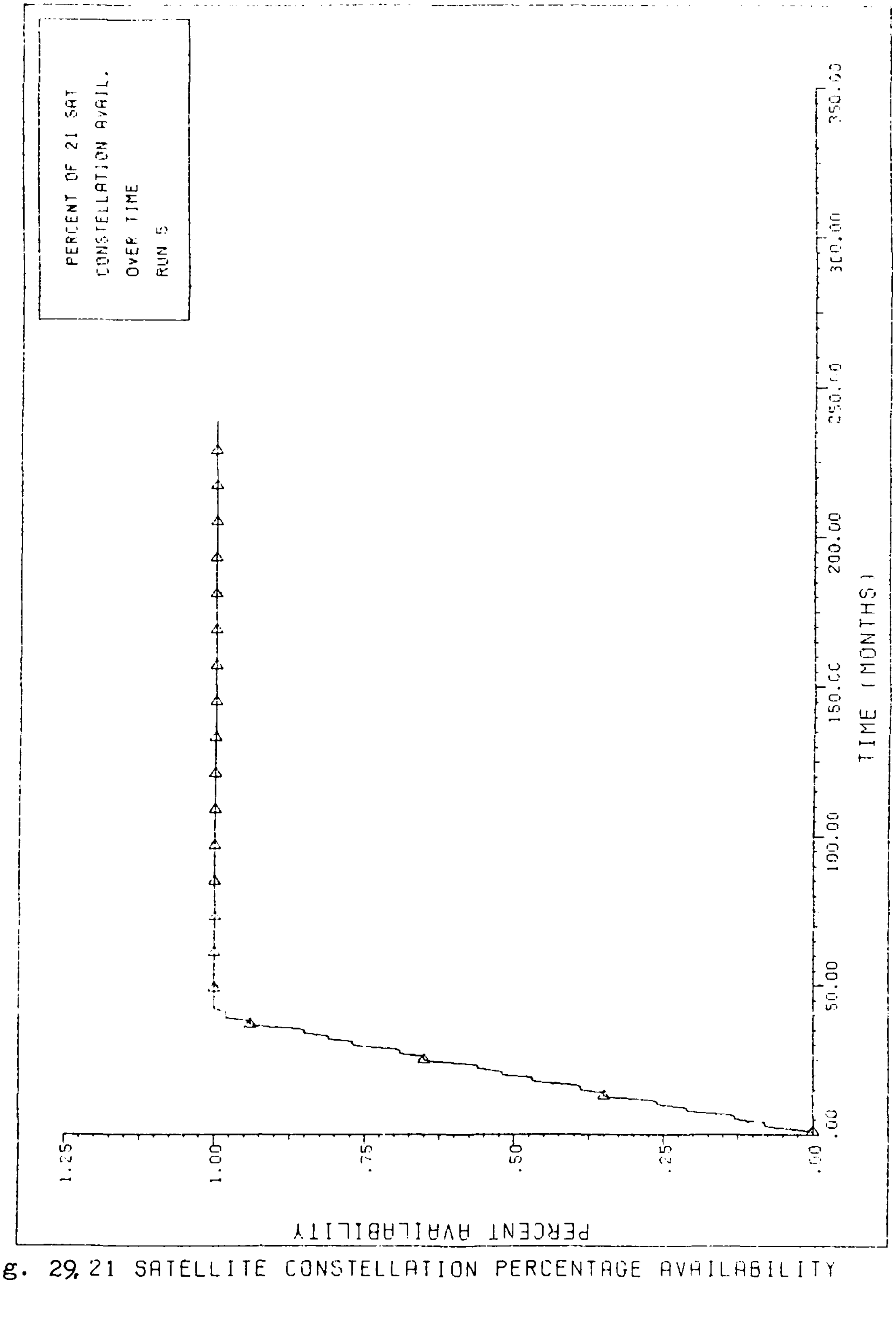


Fig. 28, 21 SATELLITE CONSTELLATION PERCENTAGE AVAILABILITY



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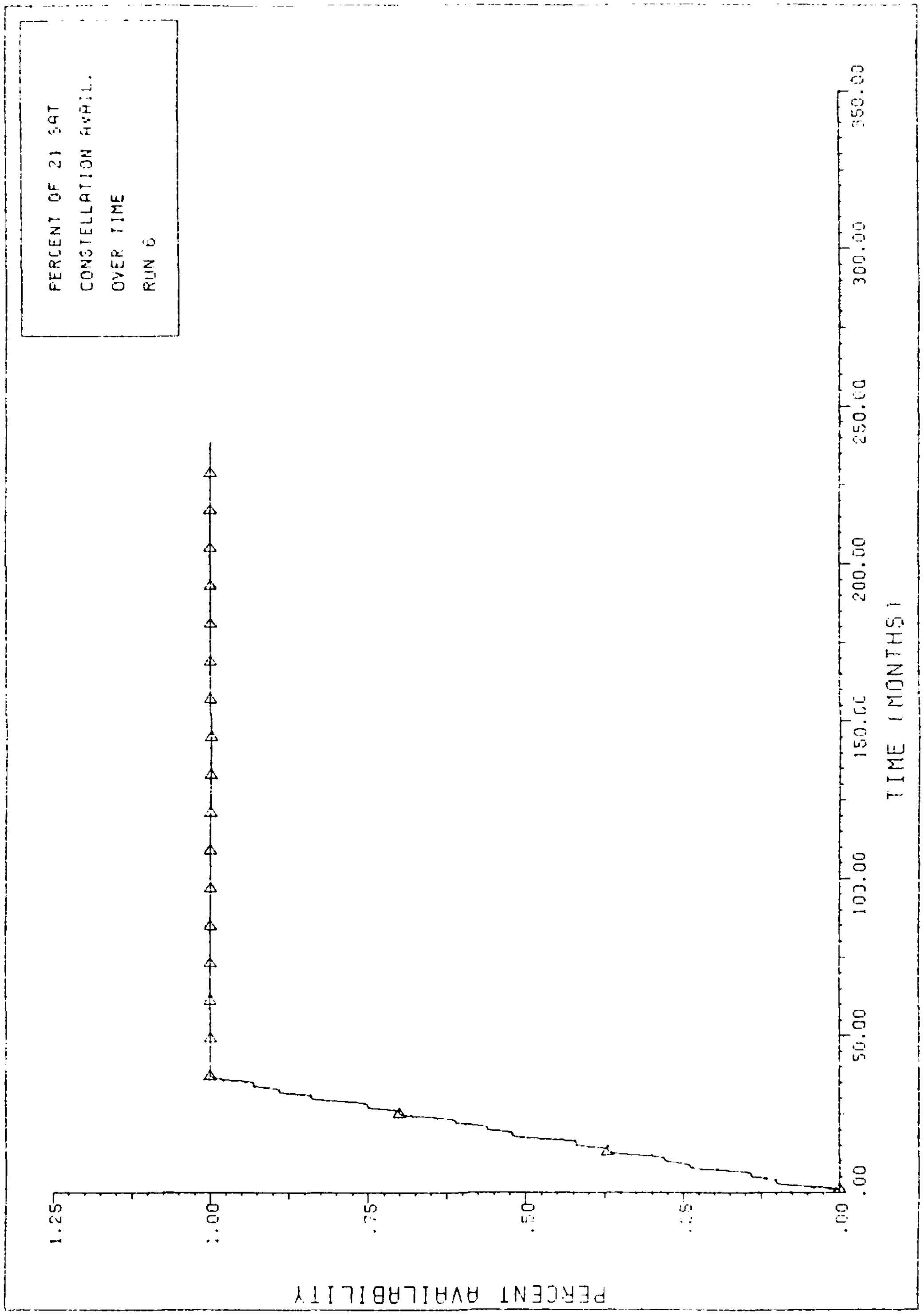

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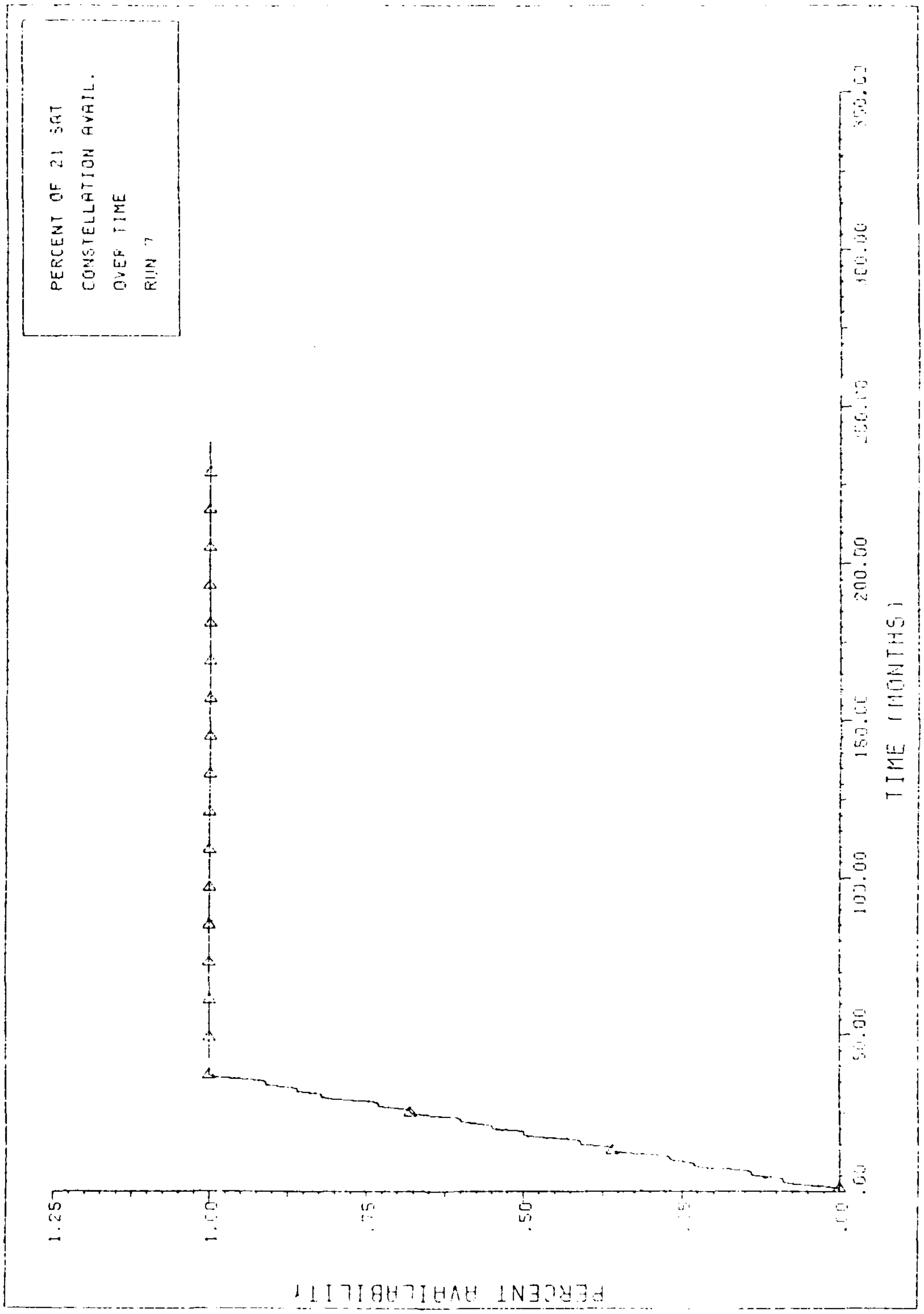

Fig. 31.21 SATELLITE CONSTELLATION PERCENTAGE AVAILABILITY

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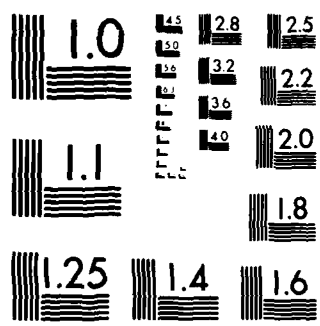

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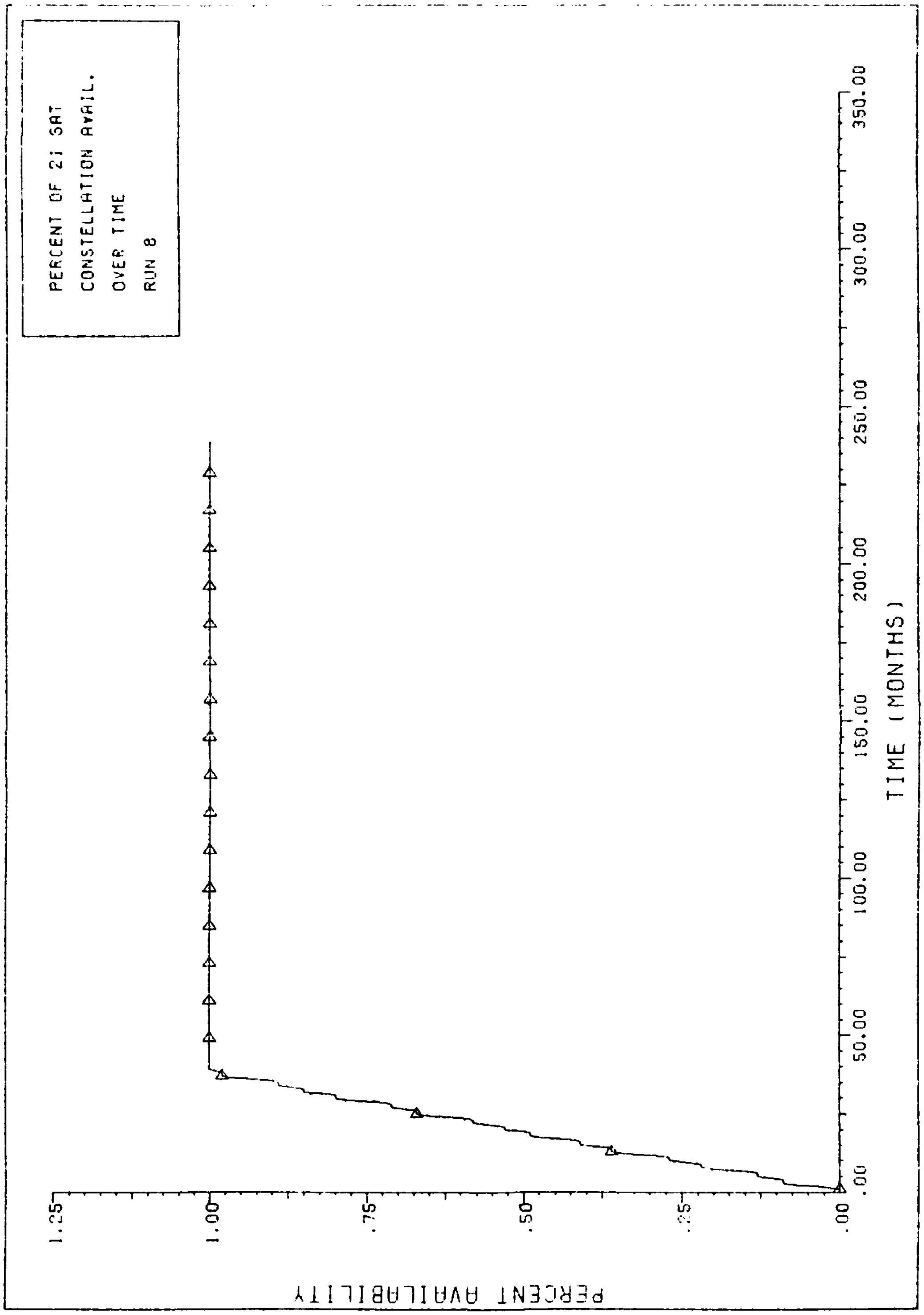
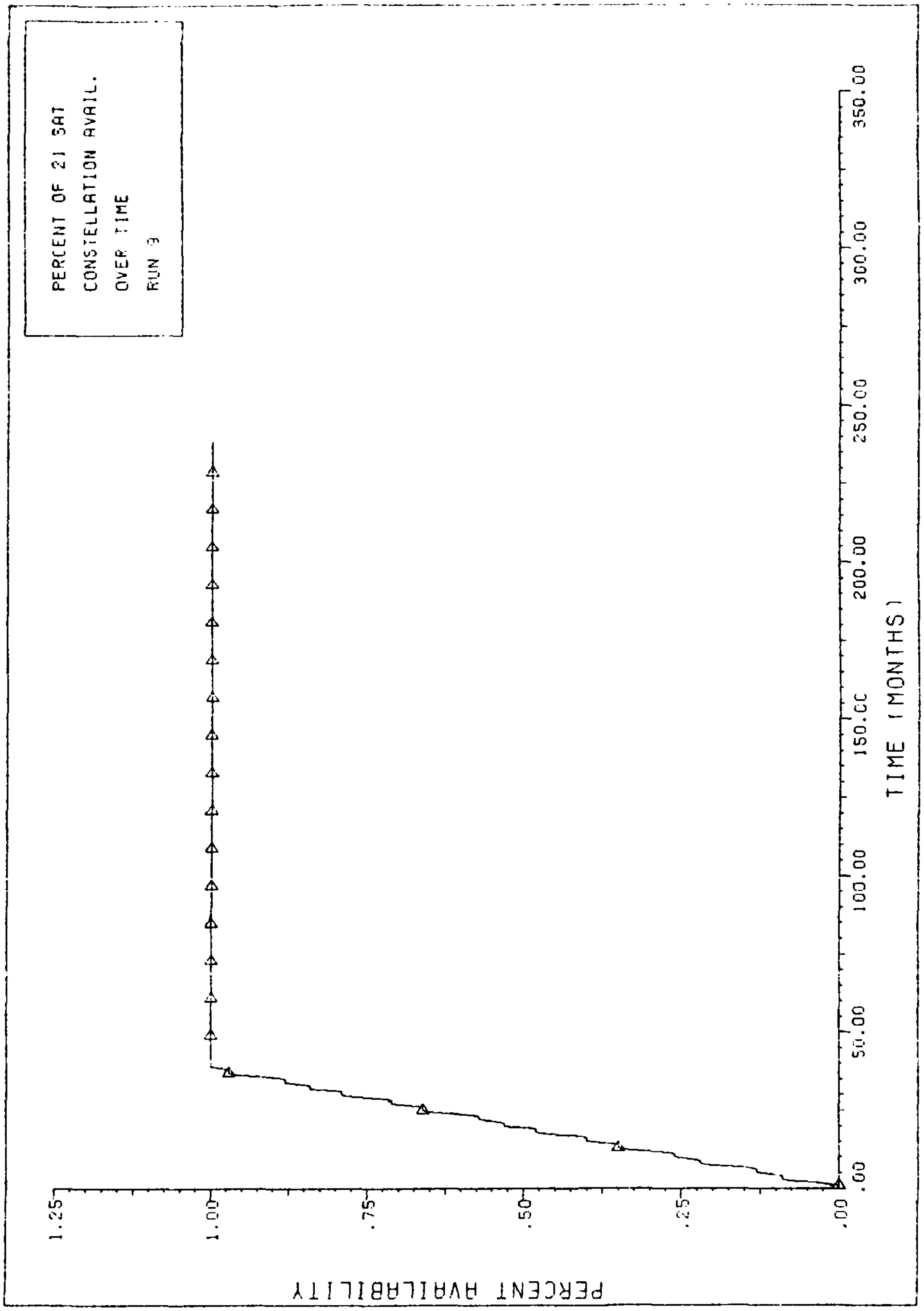


Fig. 32,21 SATELLITE CONSTELLATION PERCENTAGE AVAILABILITY



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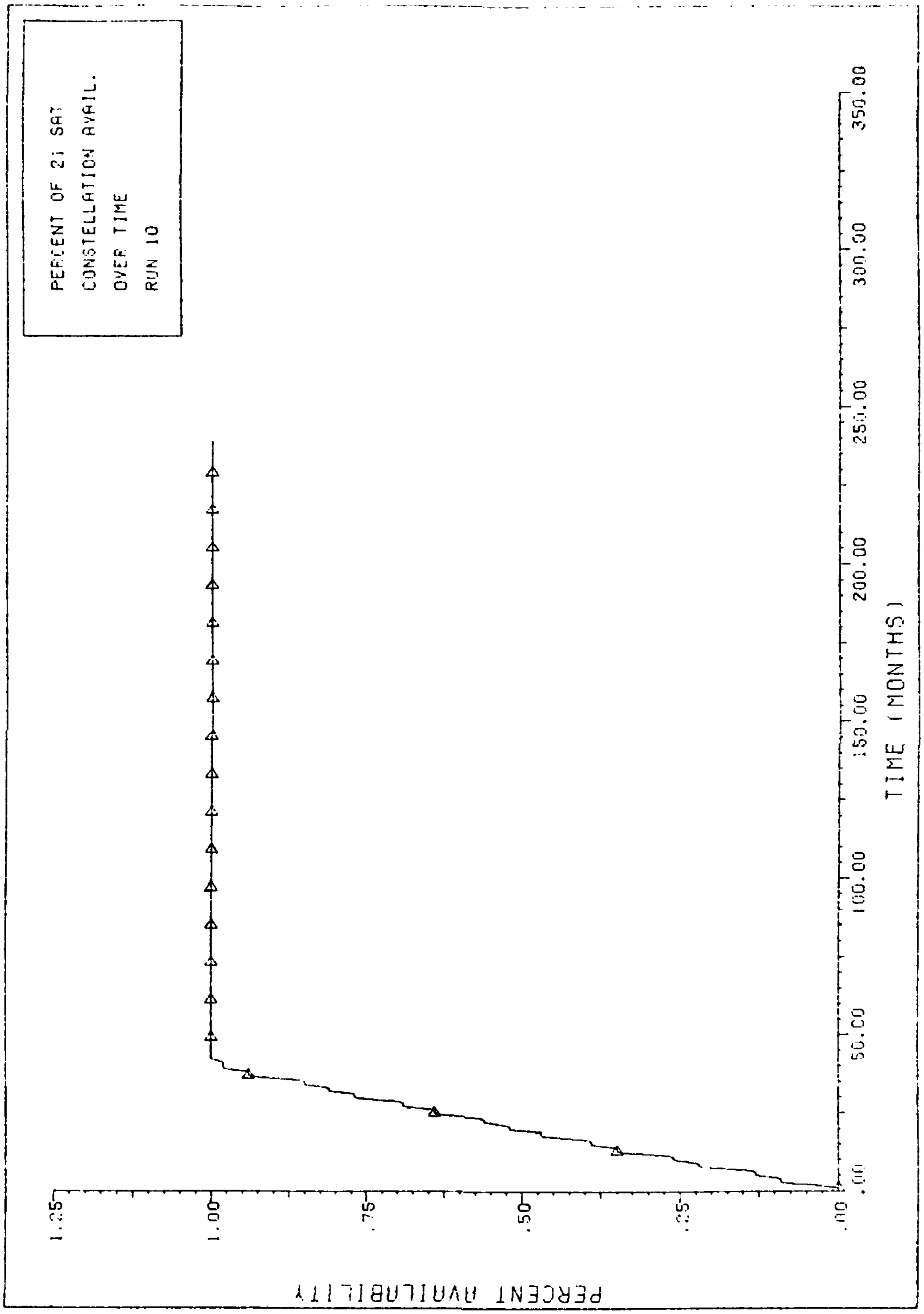

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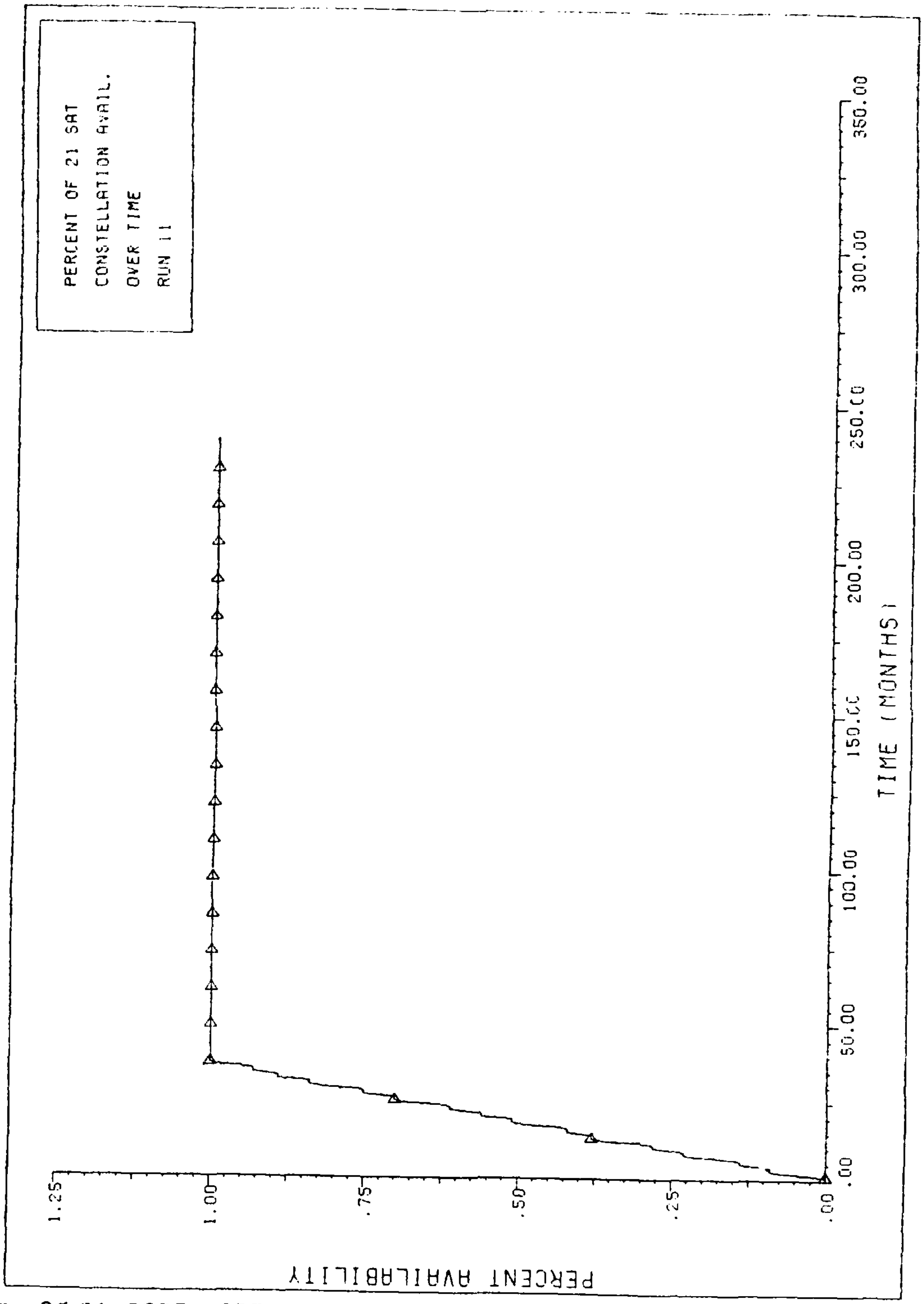

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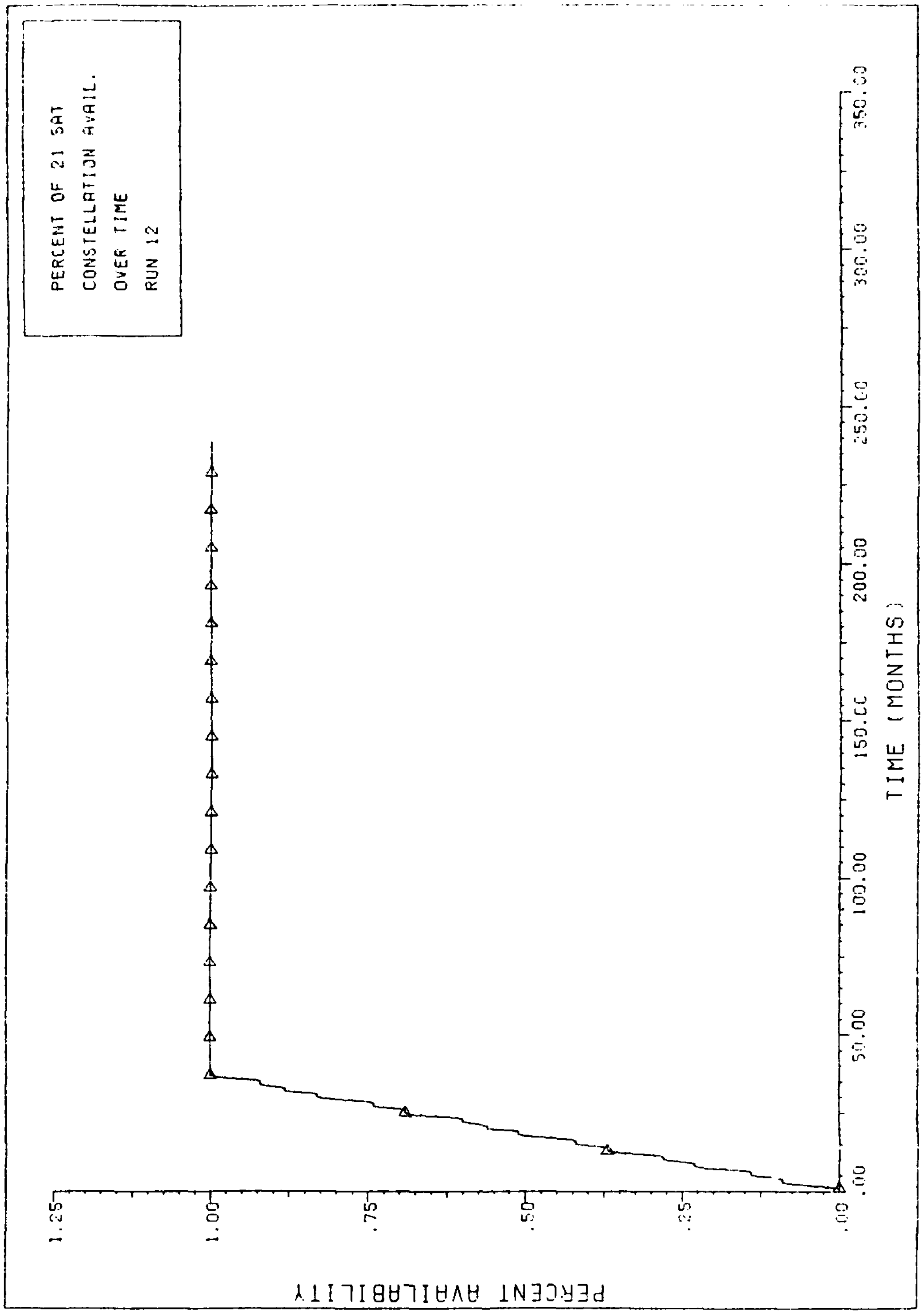

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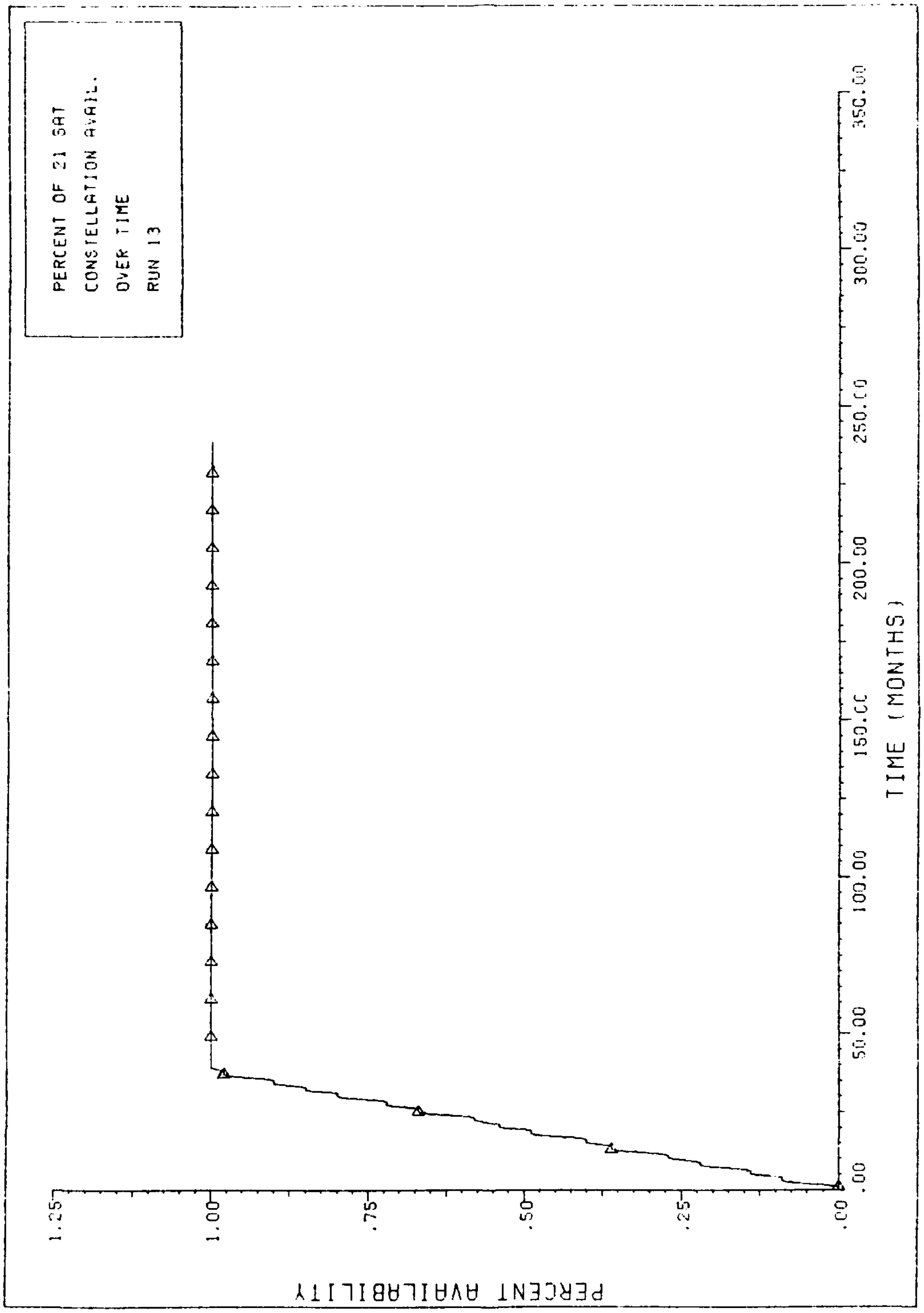

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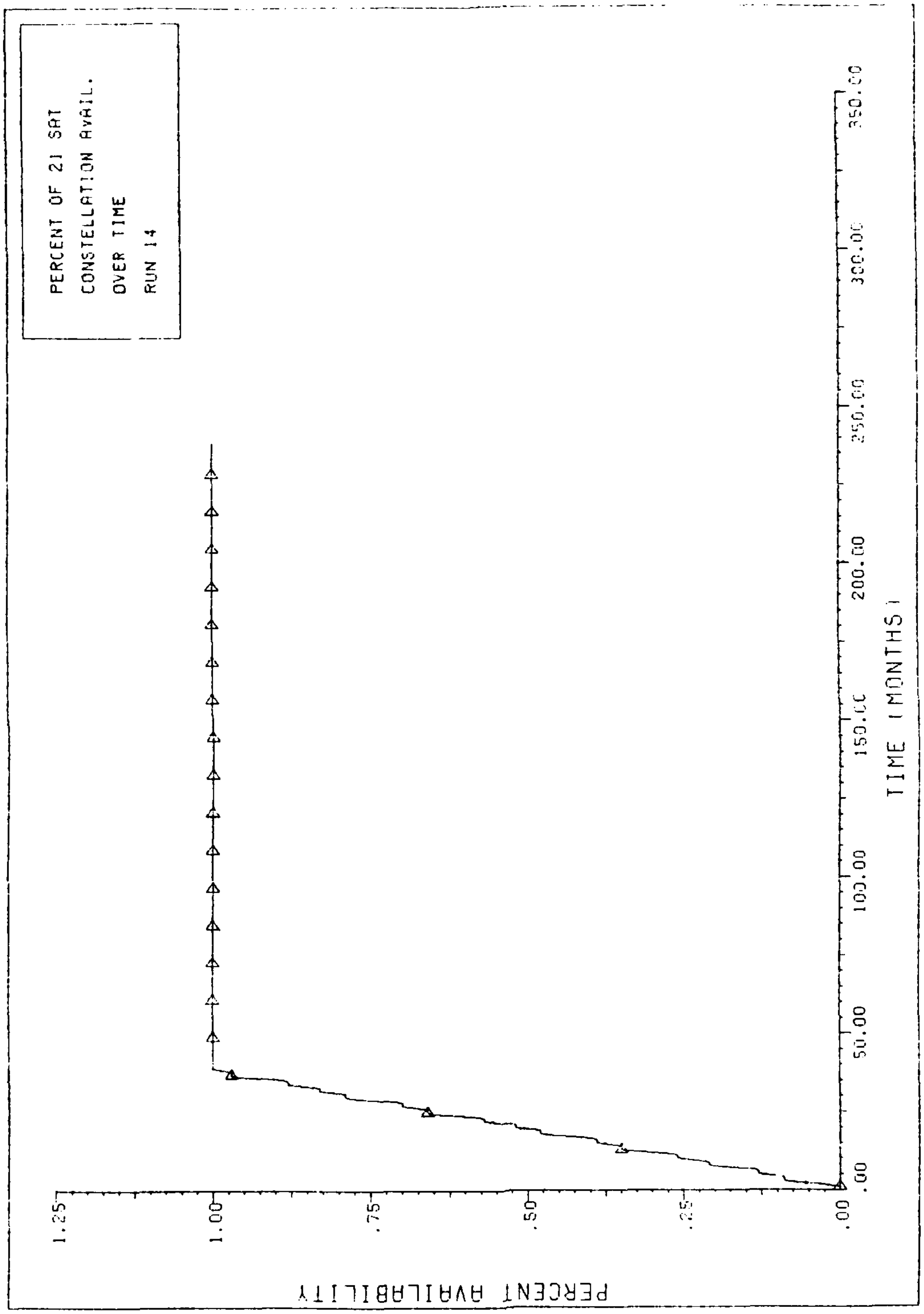

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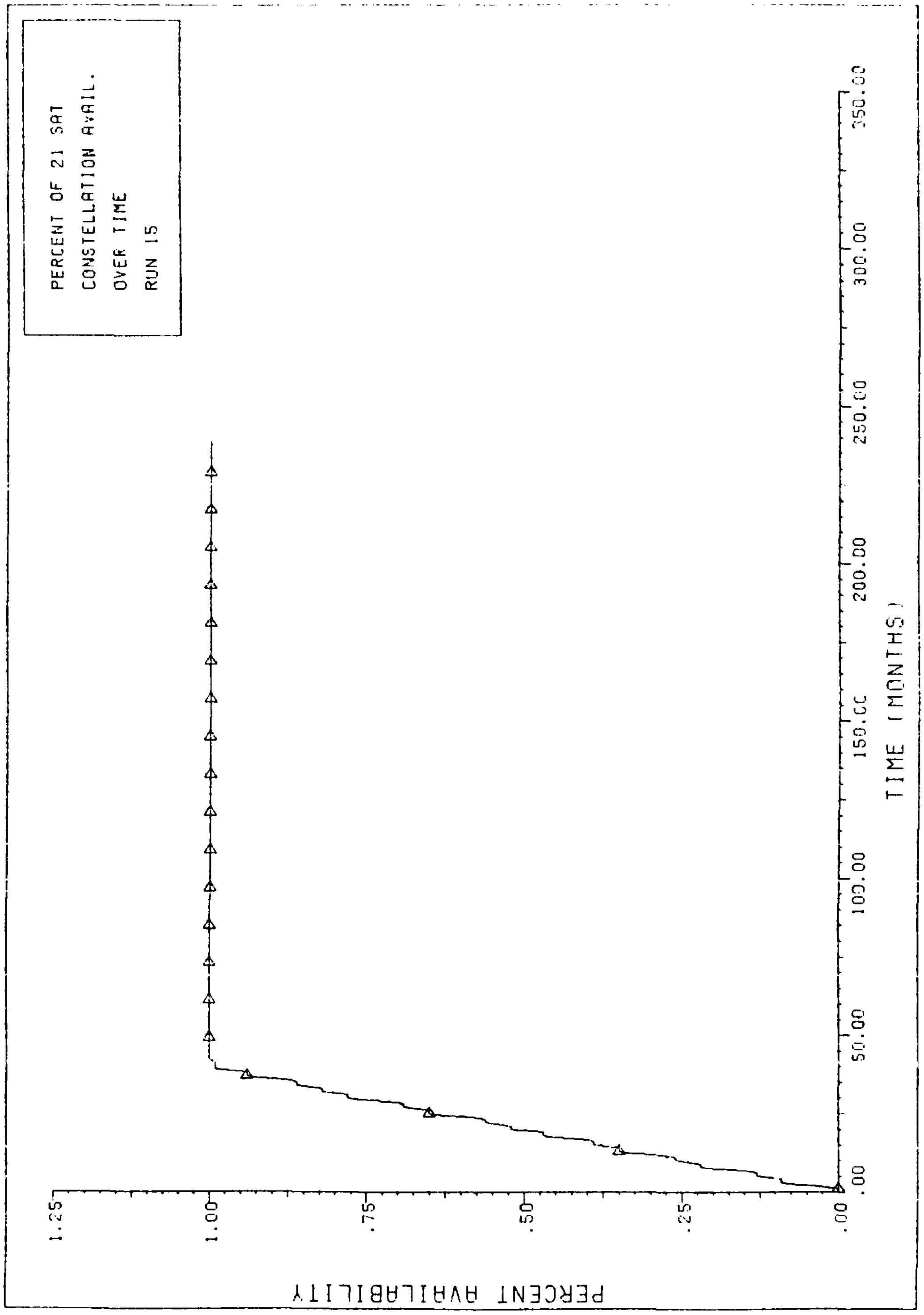

Fig. 39. 21 SATELLITE CONSTELLATION PERCENTAGE AVAILABILITY

Appendix E: Satellite Availability Curves, No Replenishment

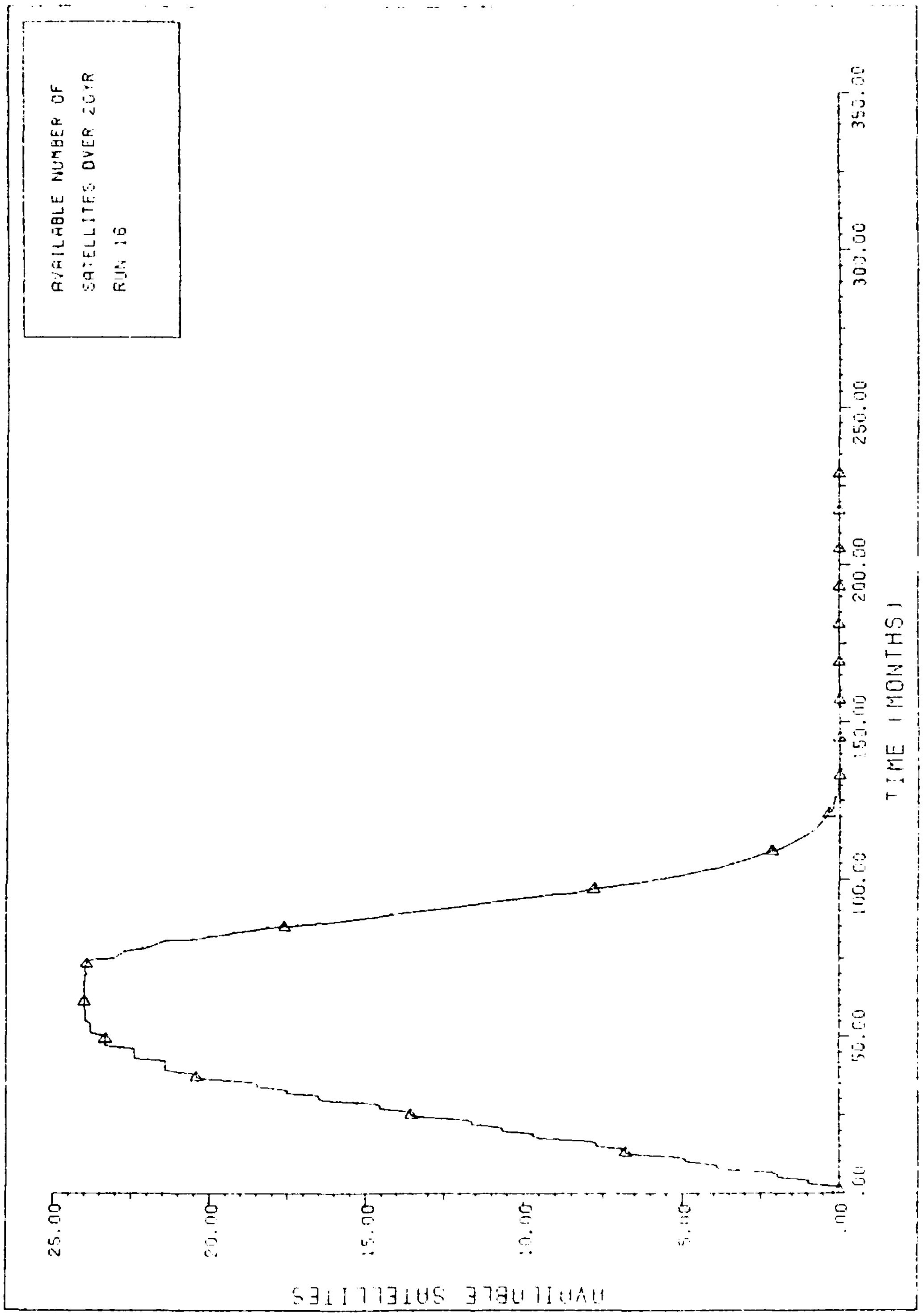

Fig. 40. SATELLITE AVAILABILITY OVER 20 YEARS. RUN 16

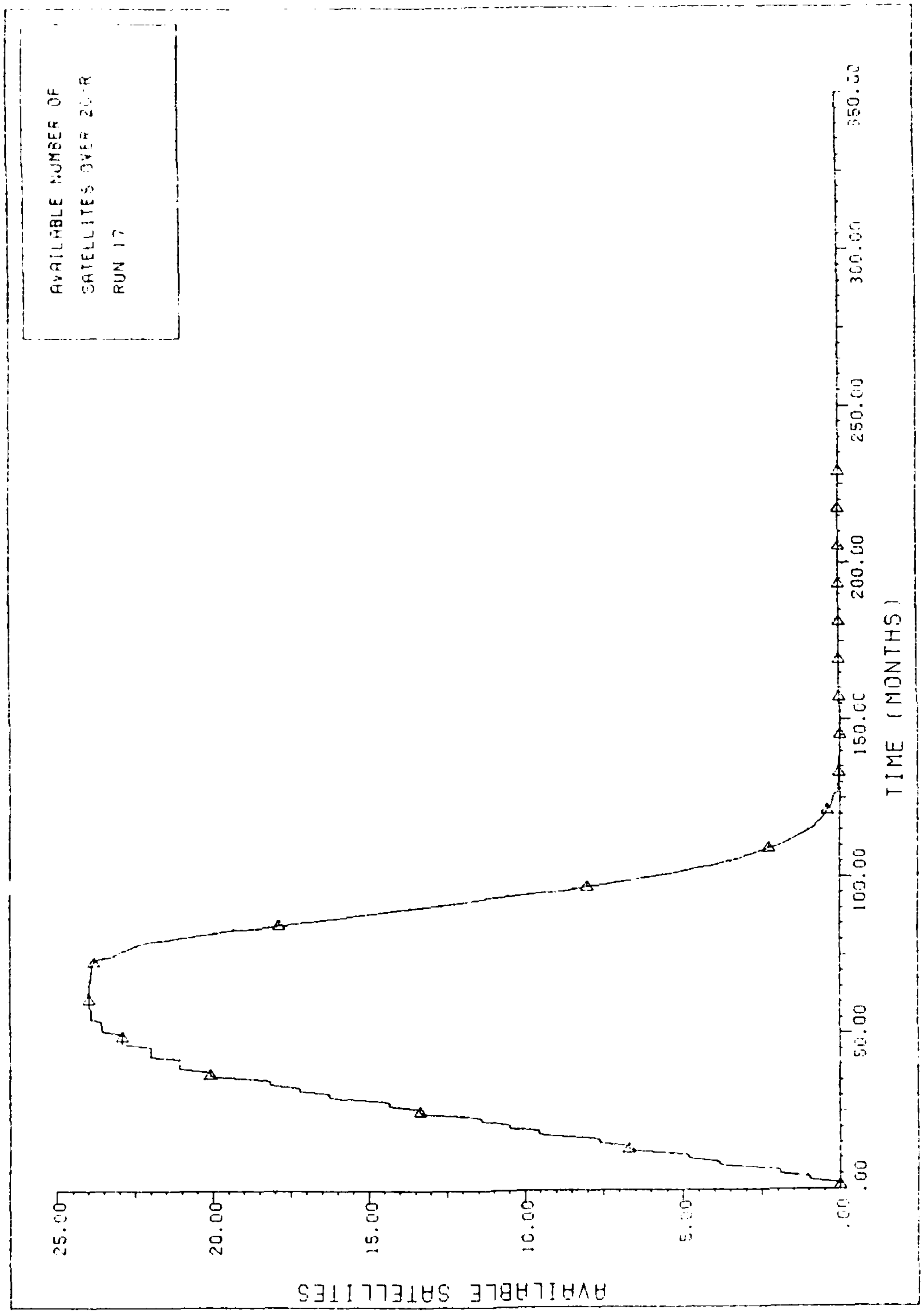

Fig. 41. SATELLITE AVAILABILITY OVER 20 YEARS. RUN 17

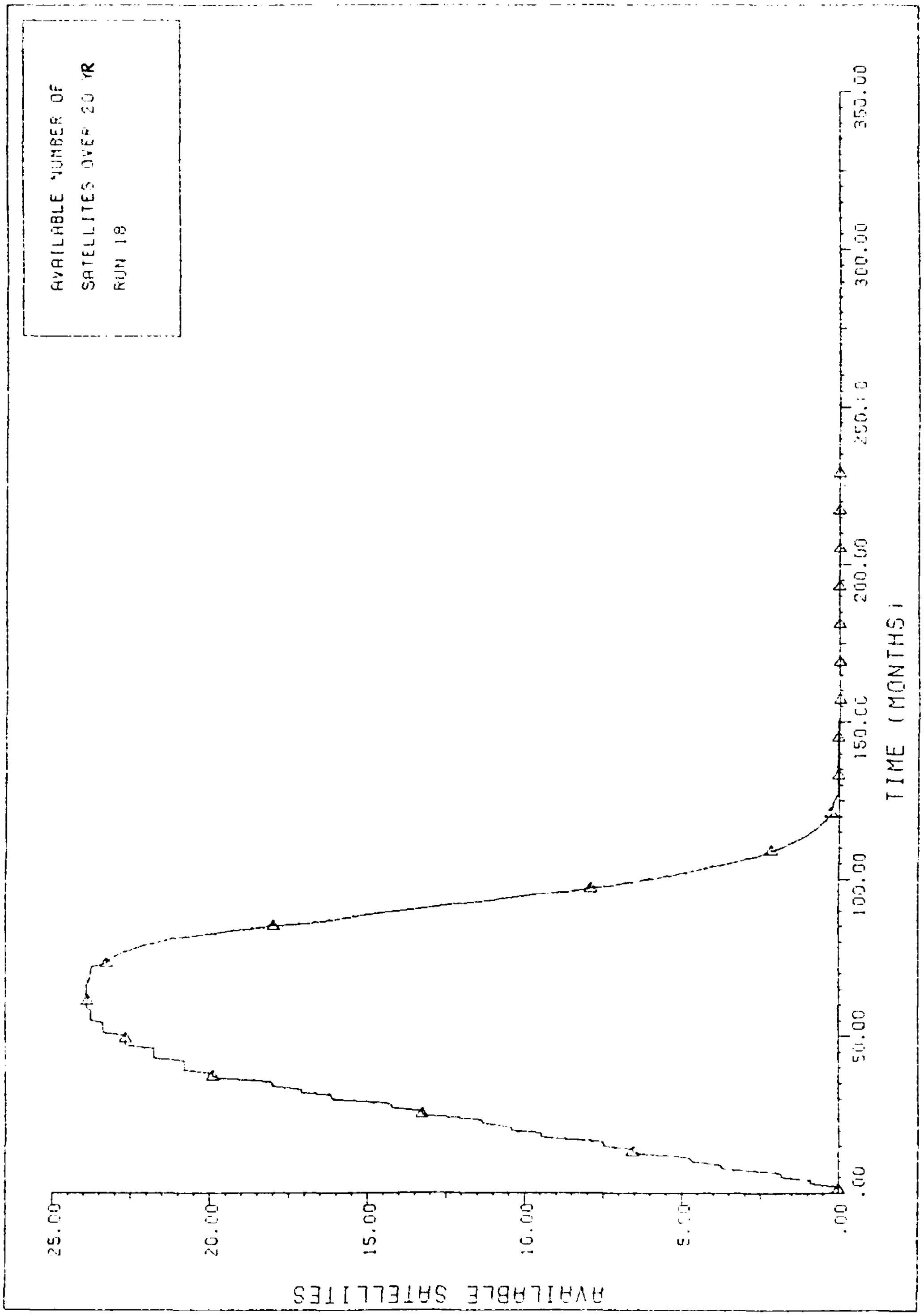

Fig. 42. SATELLITE AVAILABILITY OVER 20 YEARS, RUN 18

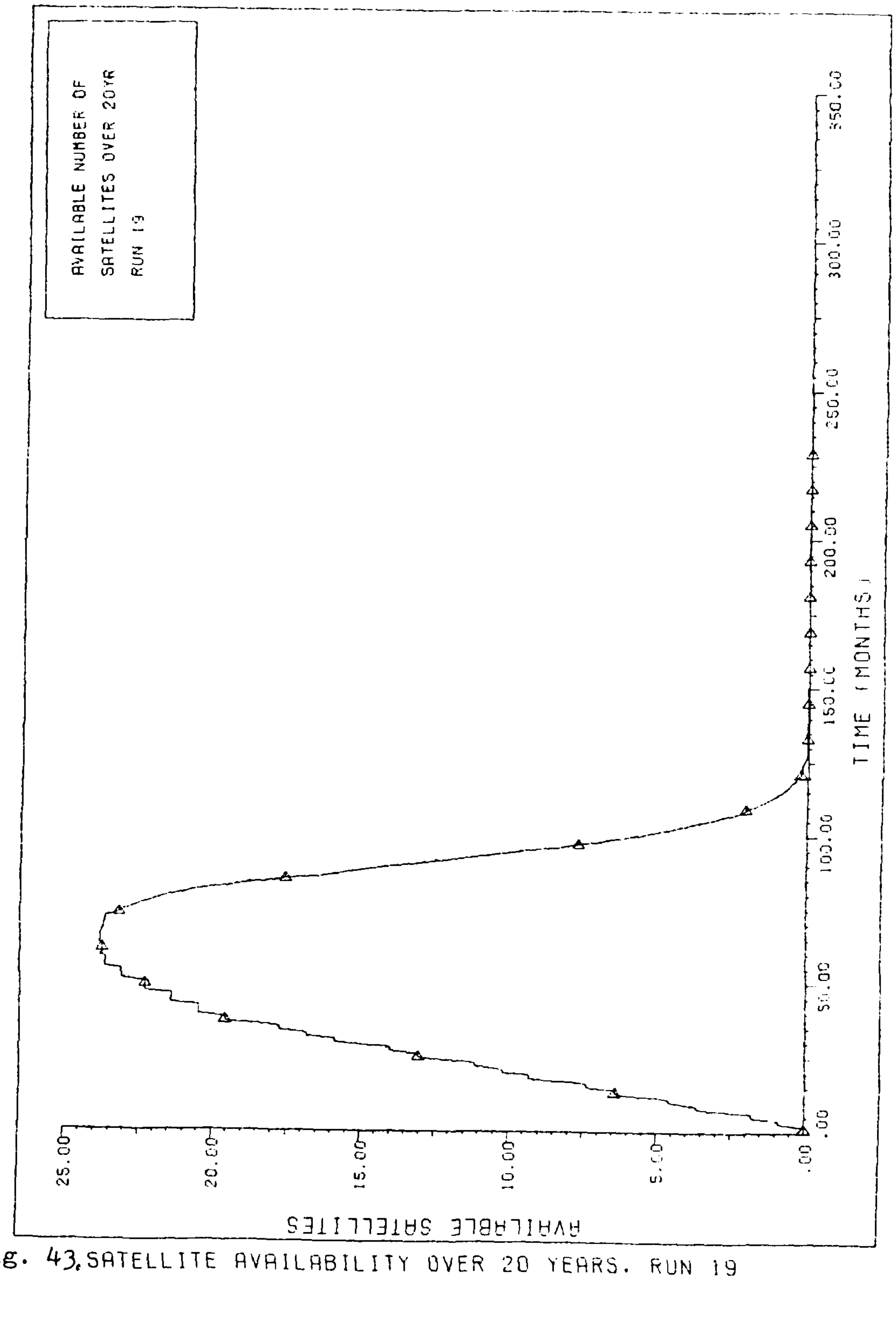

Fig. 43. SATELLITE AVAILABILITY OVER 20 YEARS. RUN 19

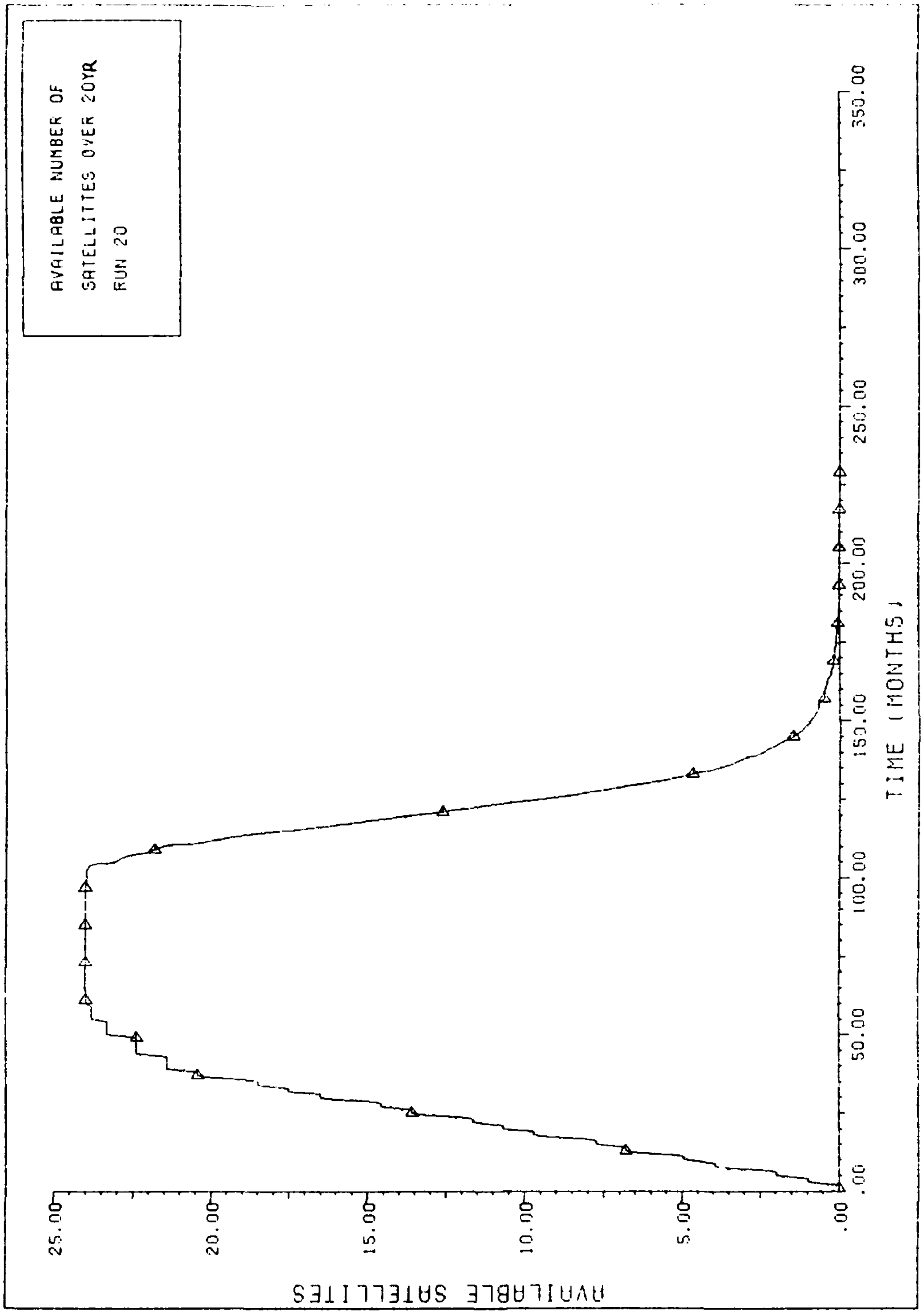

Fig. 44. SATELLITE AVAILABILITY OVER 20 YEARS. RUN 20

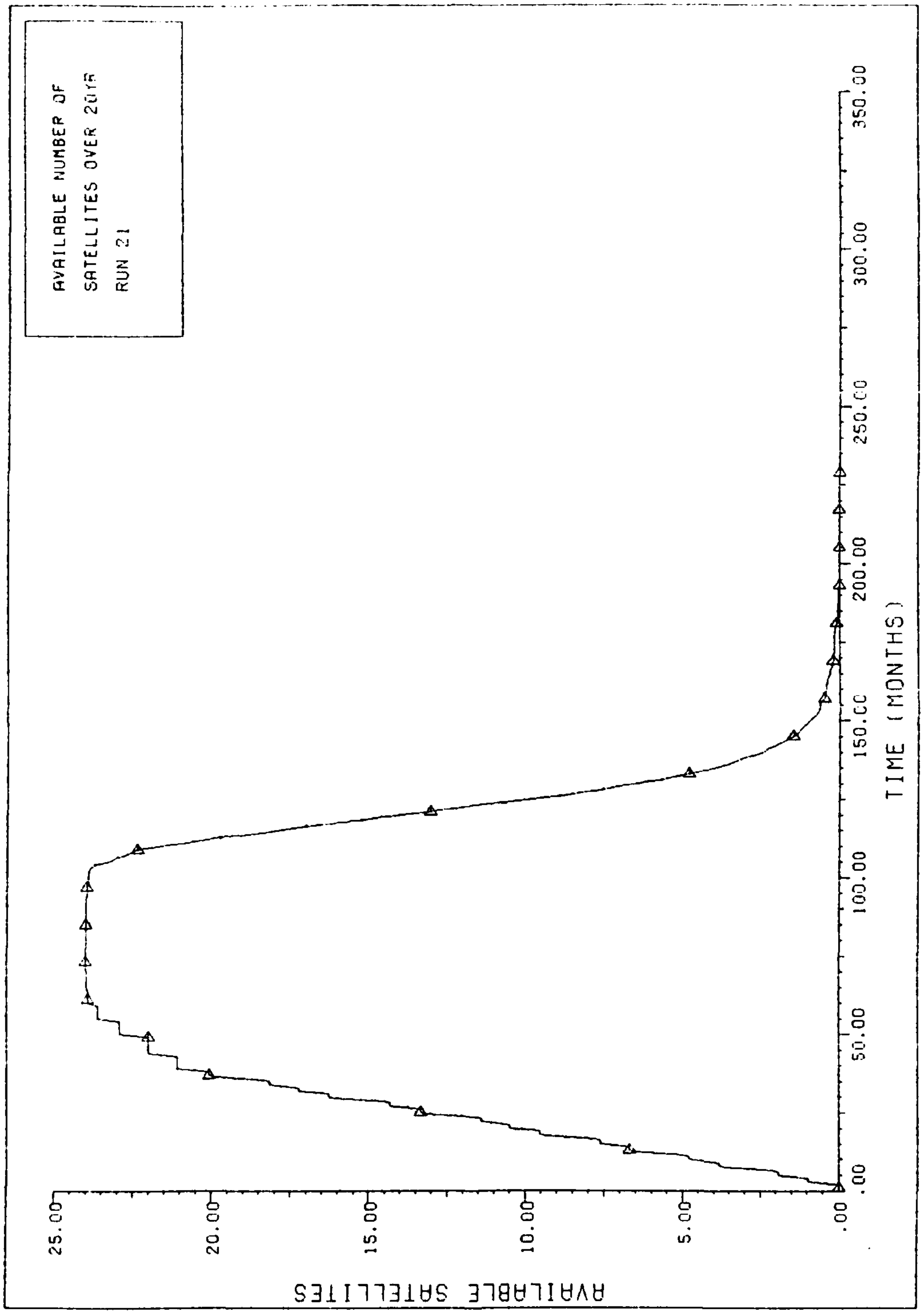

Fig. 45. SATELLITE AVAILABILITY OVER 20 YEARS, RUN 21

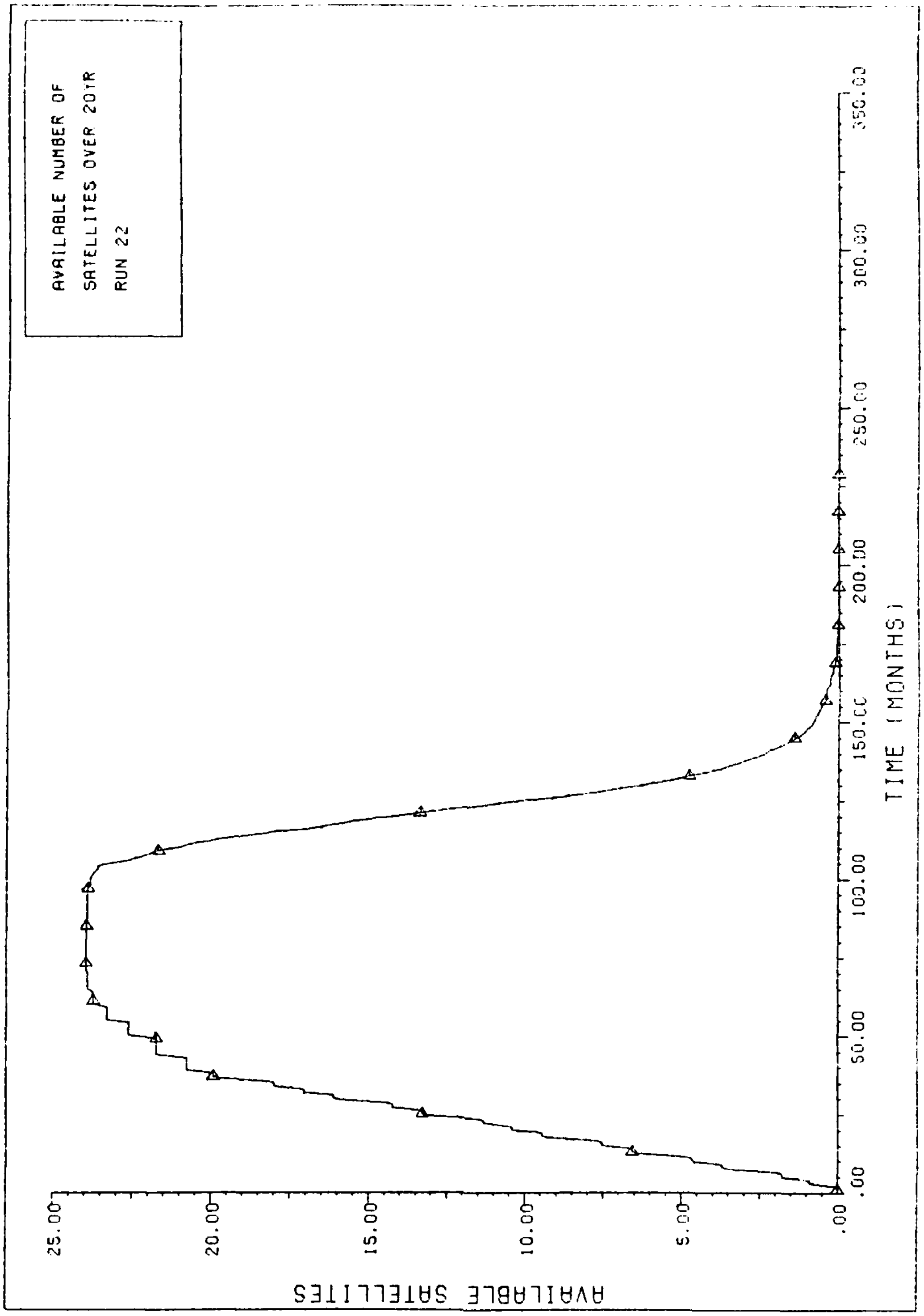

Fig. 46. SATELLITE AVAILABILITY OVER 20 YEARS. RUN 22

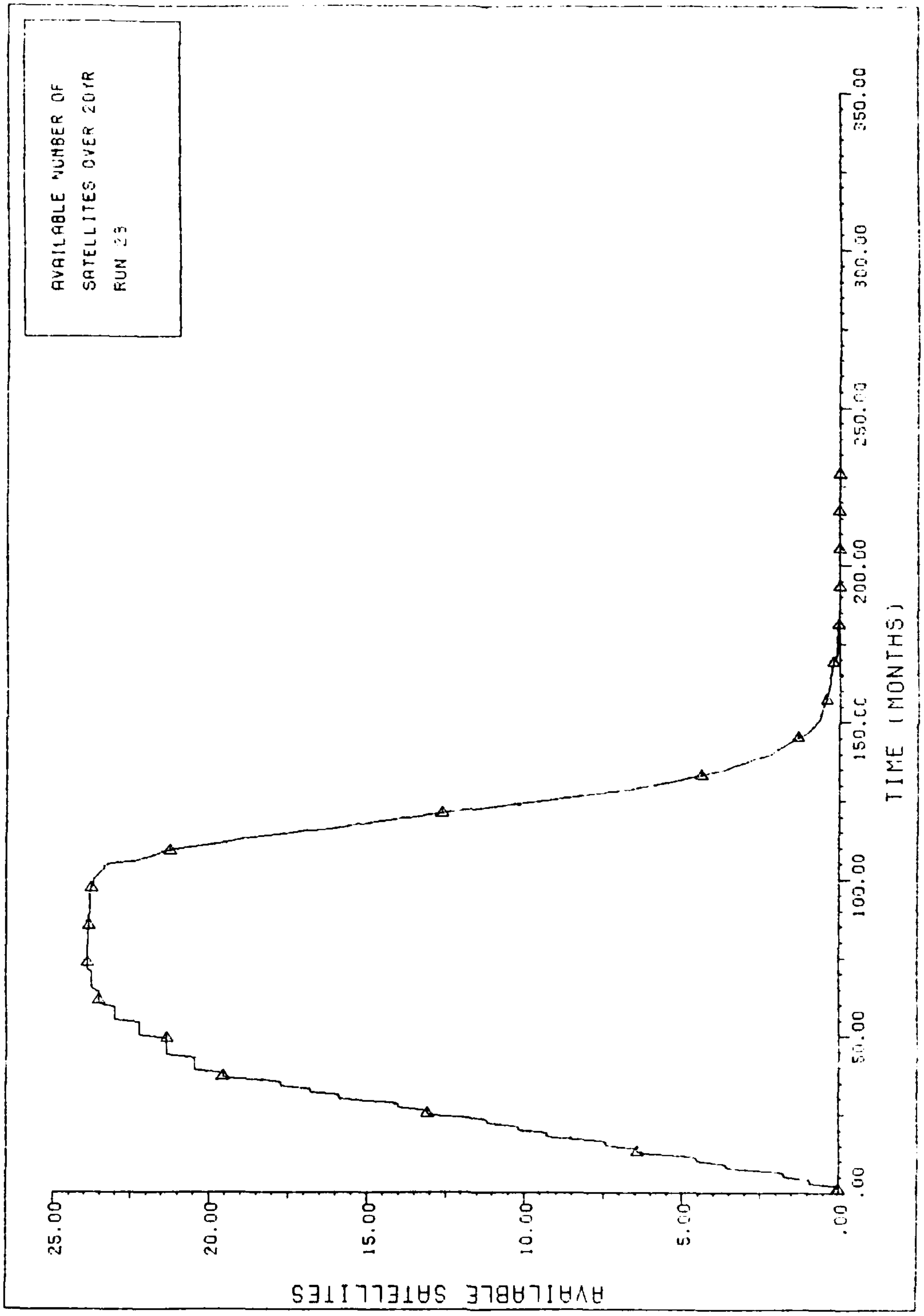

Fig. 47. SATELLITE AVAILABILITY OVER 20 YEARS. RUN 23

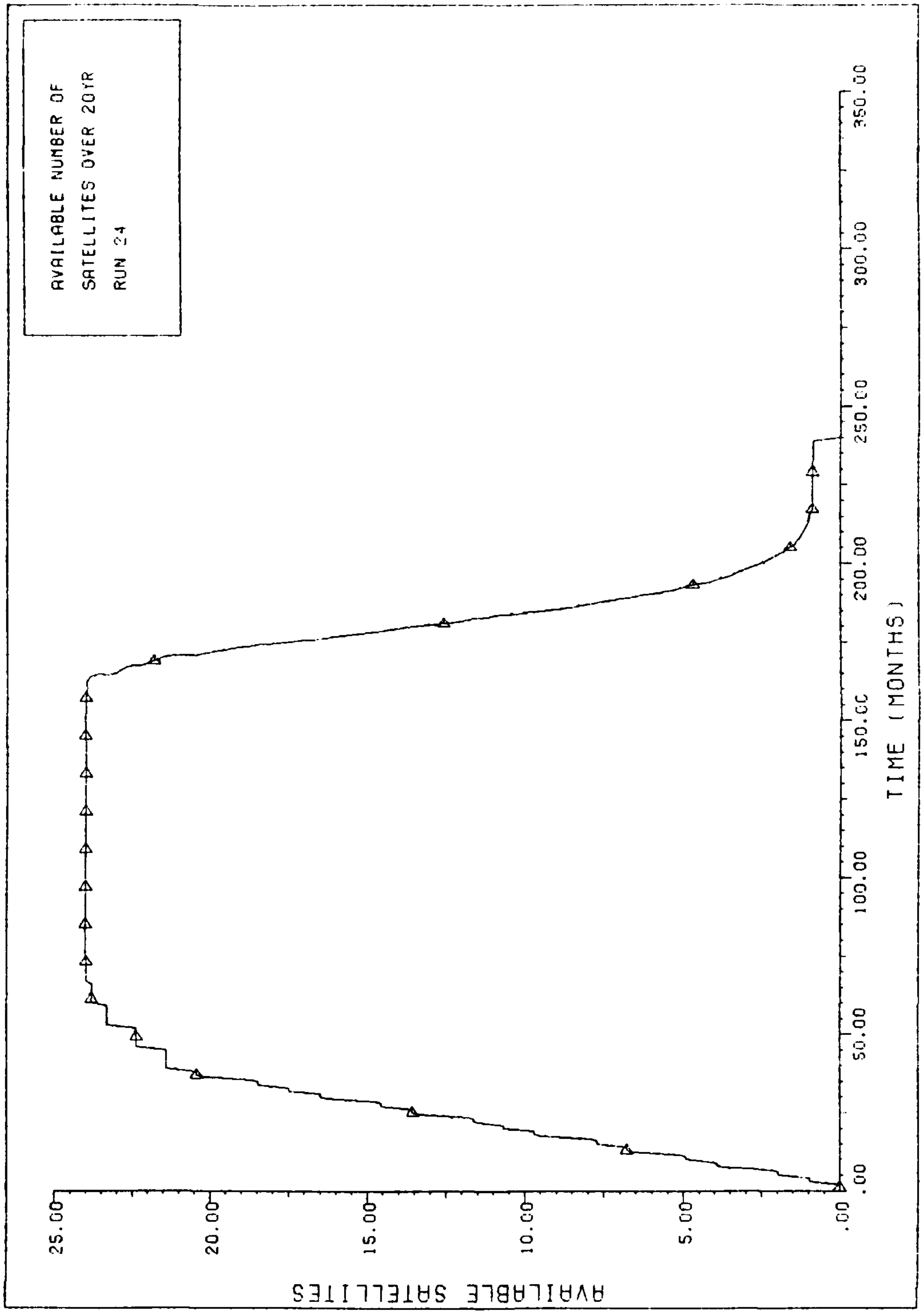

Fig. 48. SATELLITE AVAILABILITY OVER 20 YEARS. RUN 24

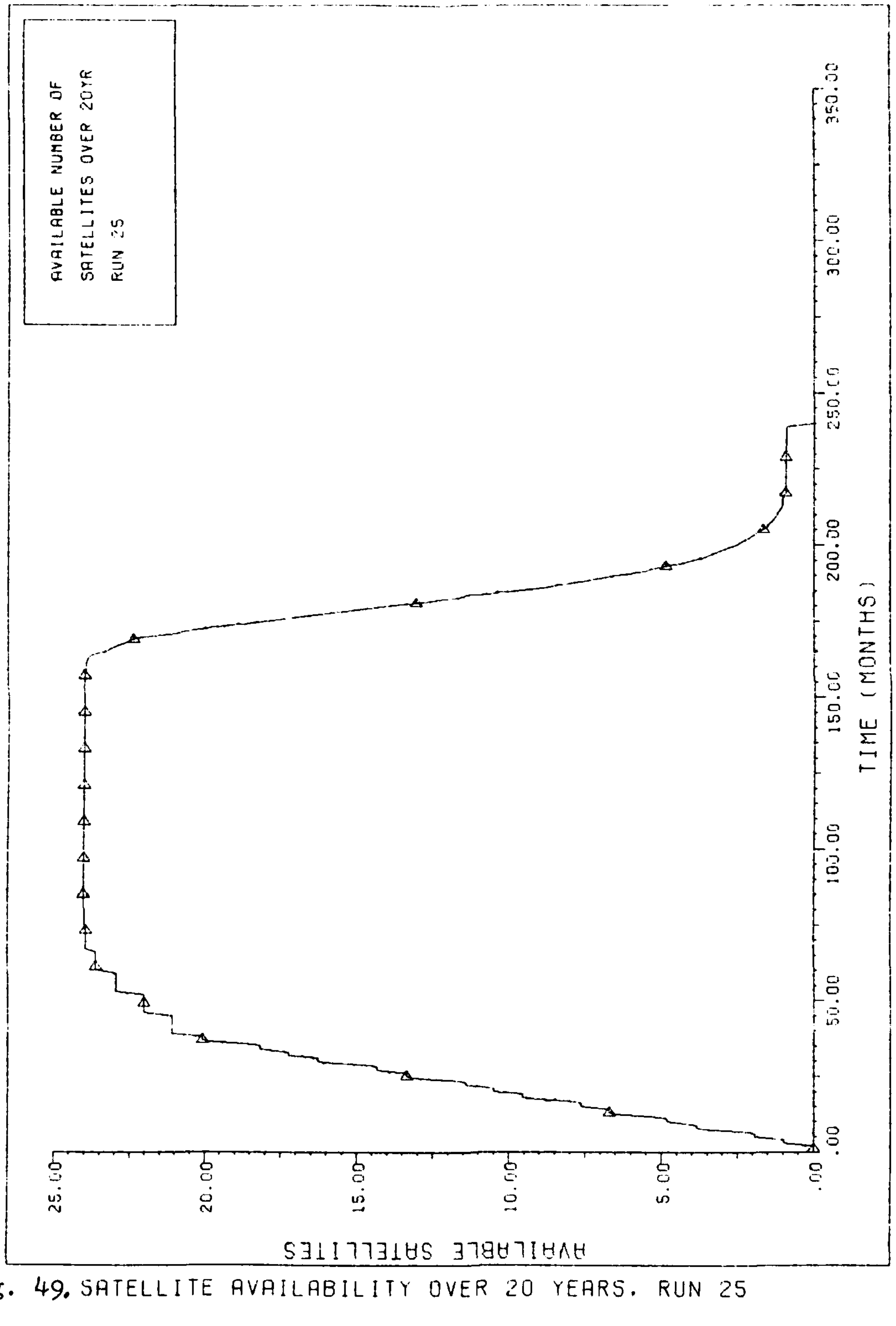

Fig. 49. SATELLITE AVAILABILITY OVER 20 YEARS. RUN 25

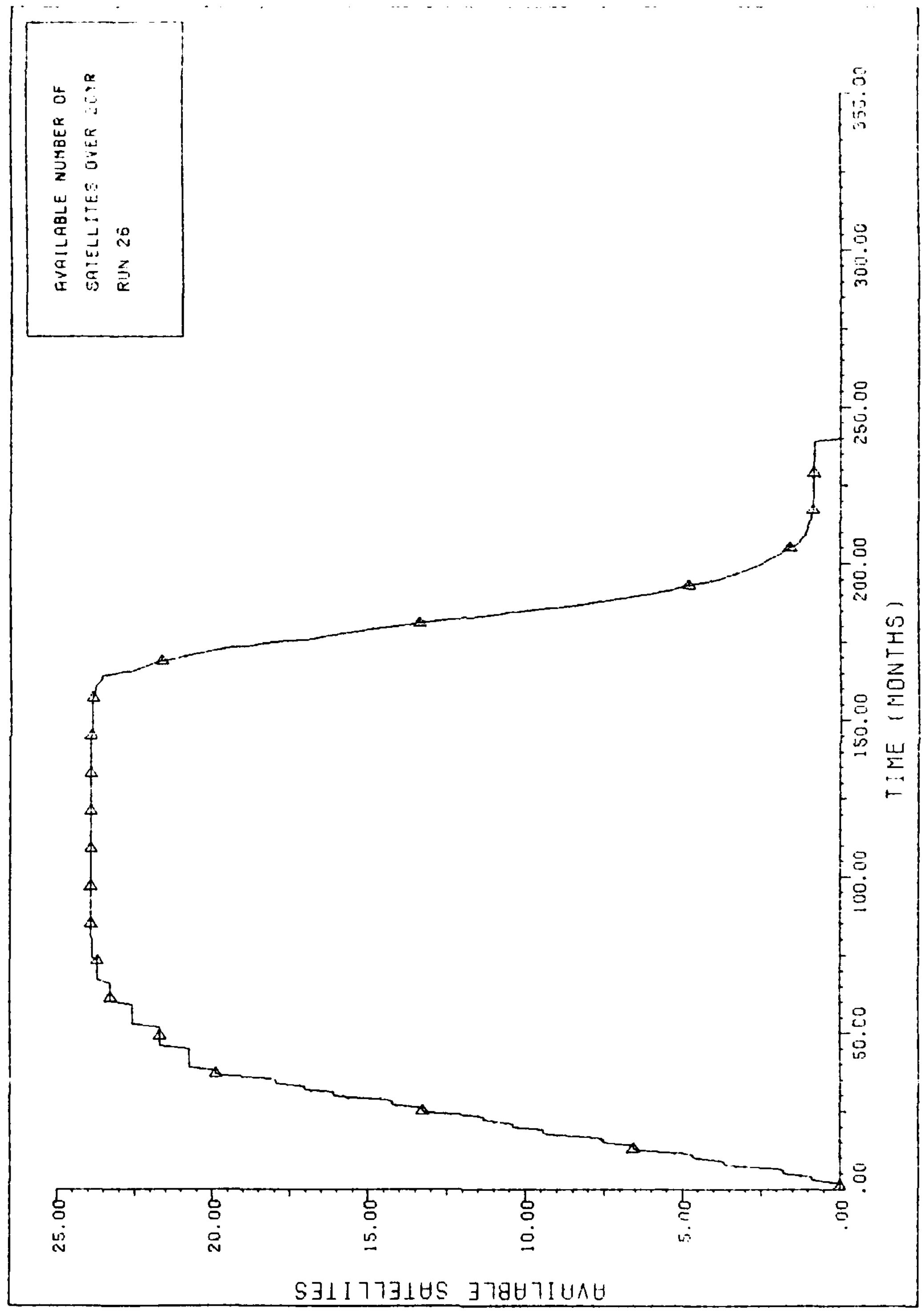

Fig. 50. SATELLITE AVAILABILITY OVER 20 YEARS. RUN 26

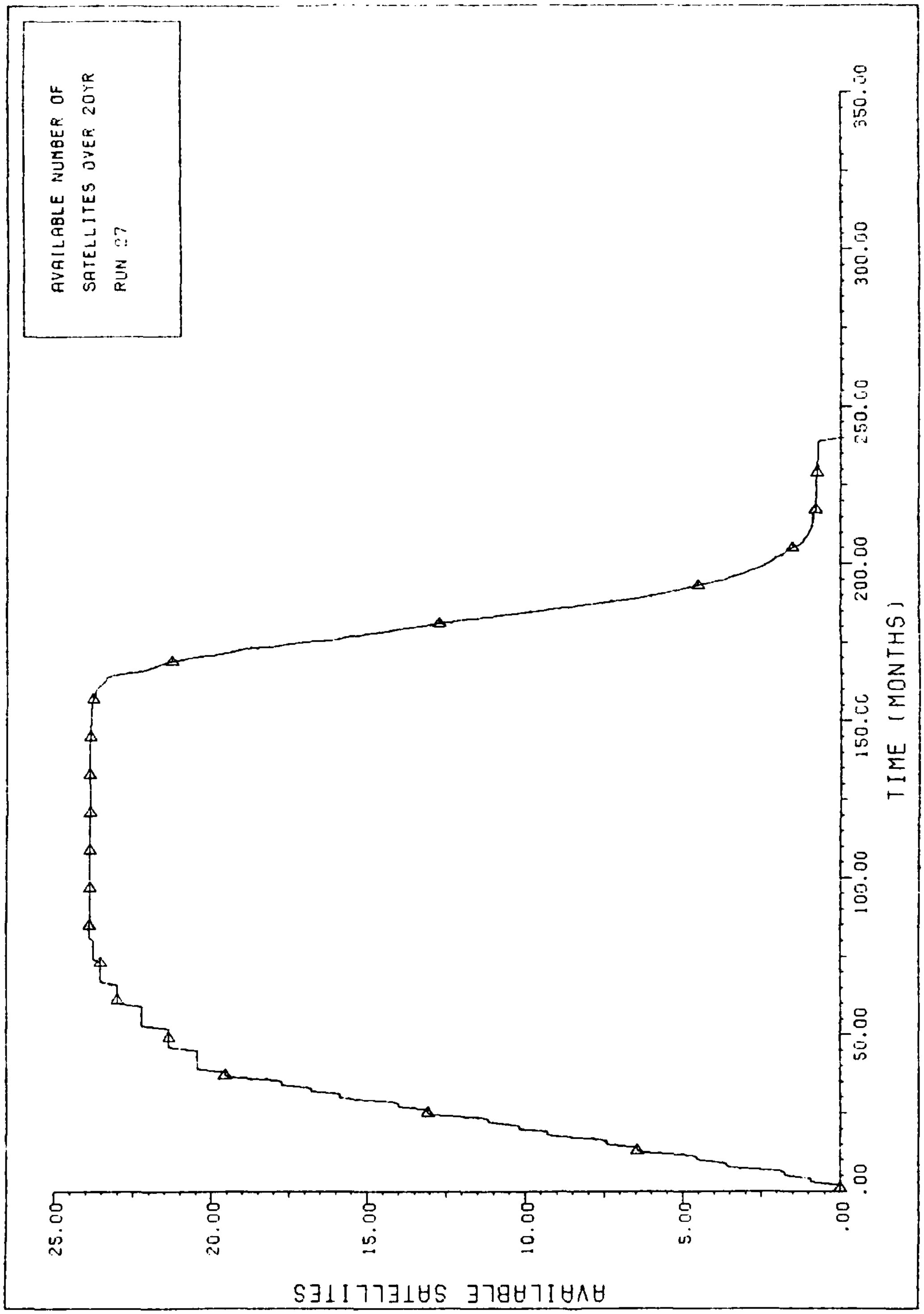

Fig. 51. SATELLITE AVAILABILITY OVER 20 YEARS. RUN 27

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TITLE: A REPLENISHMENT PHASE STUDY FOR THE NAVSTAR GLOBAL POSITIONING SYSTEM

THESIS ADVISOR: Joseph Coleman, Lt Col, DBA, USAF
William Wiesel, PhD

A Q-GERT simulation model was designed to estimate the replenishment phase for the Global Positioning System using the original block buy of 28 satellites. Block I satellites were not considered in the study. The model determines the best fixed launch schedule without replenishment to find out when the initial constellation falls below 18 satellites. Additionally, the model was modified to determine the best fixed launch schedule that would maintain the constellation at 21 functional satellites 99% of the time.

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Sensitivity analysis was performed on the parameters of satellite design life and reliability through final orbit insertion. Satellite availability curves were used to show the number of operational satellites over time. Point availability curves were used to display the fraction of 21 satellites available each month of operation.

A satellite attrition analysis was performed by selecting up to three satellites for deletion and evaluating coverage over the major land areas.

The Aerospace's EGAD Model was used to examine the performance of the Walker 18/6/2 plus 3 spares constellation. This threshold of 21 satellites became the design constraint for the simulation model of the system's operational phase over a 20 year period. A replenishment launch schedule was evaluated using a satellite design life of 7.5 years and a reliability through final orbit insertion of 94%.

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